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EFFECTS OF WEIGHT CARRIED BY SOLDIERS: COMBINED ANALYSIS OF FOUR STUDIES ON MAXIMAL PERFORMANCE, PHYSIOLOGY, AND BIOMECHANICS

by

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14. ABSTRACT
Data from four studies of standard and prototype load-carriage equipment were analyzed to determine the effects of the weight borne by male and female load carriers on time to traverse a 3.2- km course at maximal speed and on energy expenditure and kinetic and kinematic variables during externally paced walking at 4.8 km-hr $^{-1}$. The equipment configurations included fighting, approach, and sustainment loads, with masses varying from 12 kg to 50 kg. It was found that course completion times and energy expenditure were directly related to the weight carried. Kinetic variables, including ground and joint reaction forces, generally evidenced substantial linear relationships with the weight carried. Increases in maximum ankle, knee and hip joint reaction forces approached 1 N for each 1 N increase in the weight. The effects of weight carried on the kinematic variables were more complex. They included evidence of adaptations in walking gait that are likely to aid the load carrier in maintaining stability and in absorbing the increased forces associated with increased load on the body.

15. SUBJECT TERMS

ARMY PERSONNEL	BIOMECHANICS	PHYSIOLOGY	DISMOUNTED SOLDIERS
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PERFORMANCE (INDIVIDUAL)	KINEMATICS	WALKING GAITS	SOLDIER PERFORMANCE
ENERGY EXPENDITURE	KINETICS	RANGE OF MOTION	HUMAN FACTORS (ENGINEERING)

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Preface and Acknowledgements

The work reported here was conducted during the period from 1 May 2000 to 1 September 2001 by the Supporting Science and Technology Directorate, U.S. Army Natick Soldier Center (NSC), and the Military Performance Division, U.S. Army Research Institute of Environmental Medicine (USARIEM). The work was carried out under a joint NSC and USARIEM program entitled "Load Carriage Optimization for Enhanced Warfighter Performance." The program of applied research into the carrying of loads by dismounted troops has been designated a high-priority effort by the Department of Army (DA Science and Technology Objective IV.G.14) and the Department of Defense (DoD Technology Objective M12).

This report is an analysis of four studies that were conducted by NSC and USARIEM personnel at the Center for Military Biomechanics Research, U.S. Army Soldier Systems Center, Natick, MA. The references for the original studies are:

Harman, E., Frykman, P., Pandorf, C., Tharion, W., Mello, R., Obusek, J., & Kirk, J. (1999). *Physiological, biomechanical, and maximal performance comparisons of female soldiers carrying loads using prototype U.S. Marine Corps Modular Lightweight Load-Carrying Equipment (MOLLE) with Interceptor body armor and U.S. Army All-Purpose Lightweight Individual Carrying Equipment (ALICE) with PASGT body armor* (Tech. Rep. T99-9). Natick, MA: U.S. Army Research Institute of Environmental Medicine.

Harman, E., Frykman, P., Pandorf, C., Tharion, W., Mello, R., Obusek, J., & Kirk, J. (1999). *Physiological, biomechanical, and maximal performance comparisons of soldiers carrying loads using U.S. Marine Corps Modular Lightweight Load-Carrying Equipment (MOLLE), and U.S. Army Modular Load System (MLS) prototypes* (Tech. Rep. T99-4). Natick, MA: U.S. Army Research Institute of Environmental Medicine.

Obusek, J. P., & Bensel, C. K. (1997). *Physiological, biomechanical, and maximal performance comparisons of soldiers carrying light, medium, and heavy loads using the Land Warrior and the All-Purpose Lightweight Individual Carrying Equipment (ALICE) systems.* Natick, MA: U.S. Army Research Institute of Environmental Medicine. Manuscript in preparation.

Obusek, J. P., & Bensel, C. K. (1998). *Physiological, biomechanical, and maximal performance comparisons of soldiers carrying light, medium, and heavy loads using the 2nd generation of Land Warrior.* Natick, MA: U.S. Army Research Institute of Environmental Medicine. Unpublished manuscript.

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EFFECTS OF WEIGHT CARRIED BY SOLDIERS: COMBINED ANALYSIS OF FOUR STUDIES ON MAXIMAL PERFORMANCE, PHYSIOLOGY, AND BIOMECHANICS

Introduction

For purposes of planning and executing military ground operations, the items worn and carried by U.S. soldiers are divided into three configurations (Department of the Army, 1990). The fighting load configuration is the lightest in weight. It consists of mission-related equipment that is essential for immediate and short-term combat maneuvers. This configuration includes the clothing worn, a helmet, weapons, ammunition, water, a belt and a vest with pockets for carrying some of the equipment, and, possibly, a ballistic protective vest. A second configuration, the approach march load, is intended for use during prolonged, dynamic operations, such as marching to an assault point. The approach load consists of the components of the fighting load plus other items typically carried in a backpack, such as rations, a poncho, and additional ammunition and water. The third configuration, the heaviest, is the sustainment load. This configuration includes the components of the approach load plus other items, such as a sleeping bag, a change of clothes, and additional ammunition, water, and rations.

The guidelines provided to military commanders indicate that weights of the fighting and the approach load configurations should not exceed 22 kg and 33 kg, respectively. However, the components of the load configurations, and thus the weights carried by ground troops, are not prescribed by military policy. Rather, field commanders are responsible for determining the components of troops' loads after assessing mission requirements and related situational factors (Department of the Army, 1990). The multiple threats on the battlefield and the dependence of mission success on adequate supplies can result in commanders overloading their soldiers. Troops often undertake prolonged marches while carrying heavy loads and then must engage in strenuous, mission-critical activities. Historians writing on the conduct of ancient and modern military campaigns have presented numerous examples in which the weights soldiers carried resulted in loss of fighting effectiveness and failure of the mission (Cathcart, Richardson, & Campbell, 1923; Lothian, 1921a, 1921b, 1921c, 1922; Marshall, 1950/1980; Renborne, 1952).

Research has been done to quantify the impact of weight carried on soldier performance. Studies have focused mainly on the physiological effects, specifically the energy cost of carrying the load (Goldman & Iampietro, 1962; Patton, Kaszuba, Mello, & Reynolds, 1991; Pierrynowski, Winter, & Norman, 1981; Soule, Pandolf, & Goldman, 1978). There is also a growing body of work investigating the biomechanical aspects of load carriage (Kinoshita, 1985; Martin & Nelson, 1986; Pierrynowski, Norman, & Winter, 1981; Quesada, Mengelkoch, Hale, & Simon, 2000). In addition, some research

has been performed on the effects of the loads carried on maximal performance, such as times to complete either a sprint (Martin & Nelson, 1985) or an obstacle course (Holewijn & Lotens, 1992; McGinnis & Tambe, 1963). Often, the immediate impetus for undertaking a load-carriage study is to assess new equipment designs for their compatibility with military activities and acceptability to soldiers (Knapik, Harman, & Reynolds, 1996). Because of test participant availability and other logistical considerations, the number of different weights carried in a single study of this type is generally limited to three or four (Harman, Han, Frykman, & Pandorf, 2000).

A series of four, load-carriage studies was completed recently at the Center for Military Biomechanics Research, located at the U.S. Army Soldier Systems Center in Natick, MA. Each of the studies included measures of maximal performance, energy cost, and biomechanical variables, as opposed to focusing on only one of these measures. The principal purpose of the studies was to assess the effects of different designs of load-carriage systems on soldier performance. However, each system was tested using three different load weights. The four studies employed the same test protocol and the basic clothing worn by the participants was the same. Each study was a repeated measures design, with a participant being tested under all load conditions. The pooled data from the studies provided an unusual opportunity to examine the effects of a number of different load weights on an extensive array of variables. Analysis of the pooled data was undertaken and the findings are presented here.

This summary analysis of the four, original, load-carriage studies was carried out for two purposes. One was to determine how the weight of the load carried affected soldier performance over a wider range of weights and a larger array of performance measures than included previously in a single study. The second was to identify the dependent measures that were most sensitive to load weight manipulations, in anticipation of focusing on these variables in load-carriage studies planned for the near future.

Studies Analyzed

Enlisted personnel of the U.S. Army served as the participants in the studies that are the focus of this report. Three of the four studies included two load-carriage systems and the remaining study included one system. Each load-carriage system was tested in a fighting, an approach, and a sustainment load configuration. Each study was a repeated measures design, with the participants in a particular study being tested on all combinations of load-carriage system and load configuration. Information on the studies analyzed follows.

LW I vs. ALICE

In this study conducted by Obusek and Bensel (1997), the first-generation prototype of the Land Warrior system (LW I) was tested against a load-carriage system that, until August 2001, was the Army's standard system, the All-Purpose Lightweight Individual Carrying Equipment (ALICE). The LW I was an early version of an individual fighting system for dismounted soldiers that is under development. It incorporates advanced digital technology and also includes load-carriage equipment. With the LW I prototype, a rigid metal case was worn on the back as part of each load configuration. Also part of each configuration was a vest with pockets and a waist belt, which were used to carry components of the fighting load. For the approach and the sustainment loads, soft packs were attached to the metal case. With the ALICE system, a load was carried on the back only in the approach and the sustainment load configurations. The carrying equipment for these loads was a rucksack attached to an external frame. The ALICE system included a vest with pockets and a belt for carrying the components of the fighting load. Participants in this study were 12 Army enlisted men, who were infantry troops assigned to an airborne division.

LW II

Obusek and Bensel (1998) conducted this study of the second-generation prototype of the Land Warrior system (LW II). As in the first-generation version of the system (Obusek & Bensel, 1997), every load configuration included a rigid metal case that was worn on the back, along with a vest and a waist belt to accommodate components of the fighting load. Soft packs that attached to the metal case were used for the approach and the sustainment load configurations. Eleven enlisted men, all infantry troops assigned to an airborne division, participated in the study. Nine of the participants also took part in the LW I vs. ALICE study.

MOLLE vs. ALICE

In this study conducted by Harman et al. (1999a), a prototype version of the Modular Lightweight Load-Carrying Equipment (MOLLE) was tested against the ALICE system. As of August 2001, the MOLLE system replaced the ALICE as the Army's

standard load-carriage equipment. With both the MOLLE prototype used in this study and the ALICE, the approach and the sustainment configurations included a backpack, whereas the fighting load configuration did not. The fighting load was accommodated on a vest with pockets and a waist belt. Participants were 12 Army enlisted women, whose military occupations varied from the physically strenuous to the sedentary.

MOLLE vs. MLS

Harman et al. (1999b) conducted this study in which a MOLLE prototype was contrasted with the Modular Load System (MLS), another prototype load-carriage system. With both systems, a backpack was worn as part of the approach and the sustainment load configurations, but not with the fighting load configuration. Components of the fighting load were accommodated on a vest and a waist belt. Eleven male enlisted soldiers participated in testing. Six of the men were infantry troops and the remainder had recently completed initial Army training, which was comprised of basic and advanced individual training.

Table 1
Sample Size and Gender of Test Participants and Means (and SDs) of Height, Weight, and Age for Test Participants and for Larger Samples of U.S. Army Men and Women

Study	Height (cm)	Body Mass (kg)	Age (years)	*N*	Gender
LW I vs. ALICE	175.19 (5.65)	75.20 (13.99)	22.0 (3.1)	12	Male
LW II	175.08 (4.64)	78.34 (14.57)	22.4 (3.1)	11	Male
MOLLE vs. ALICE	165.92 (6.50)	61.26 (6.72)	25.3 (5.3)	12	Female
MOLLE vs. MLS	179.11 (5.09)	83.46 (12.20)	24.0 (4.7)	11	Male
U.S. Army Males	175.58 (6.68)	78.49 (11.10)	27.22 (6.8)	1774	Male
U.S. Army Females	162.94 (6.36)	62.01 (8.35)	26.19 (5.7)	2208	Female

In all the studies, a principal or assistant investigator briefed the potential volunteers, and informed consent was obtained from those who chose to participate. The studies were conducted in accordance with Army Regulation 70-25 (Use of Volunteers as Subjects of Research). The data acquisition phase of each study lasted approximately three weeks. Volunteers usually participated in one or two testing sessions a day. Each session lasted between 1 and 3 hr, including rest time and time waiting for other

volunteers to be tested. Additional information regarding the participants in each study, including means for height, weight, and age, is presented in Table 1. The means for height, weight, and age of the Army men and women in the working database derived from the 1988 anthropometric survey of U.S. Army personnel are also presented (Gordon et al., 1989).

Method

Weights Carried

For the maximal performance and the energy cost testing, the participants in each study were outfitted in the Battledress Uniform (BDU) coat and trousers, combat boots, a ballistic protective helmet, and a ballistic protective vest. They also carried a demilitarized M16 rifle in both hands in front of the body (i.e., at port arms). For the biomechanics testing, the participants wore the T-shirt and shorts of the standard Army physical training uniform, combat boots, a protective helmet, and a protective vest. The participants also carried a demilitarized M16 at port arms. The load-carriage equipment was added to these basic outfits.

The load-carriage systems used in each study were tested in three configurations, a fighting, an approach, and a sustainment load configuration. The fighting load included a water-filled canteen, simulated grenades, and simulated M16 ammunition. For the Land Warrior systems, the fighting load also included a metal case worn on the back. The case contained steel plates equal to the mass of the communication and computer equipment designed to be carried in the case. For all load-carriage systems tested, the approach load configurations consisted of the fighting load plus a backpack. Steel plates were placed at the center of volume of the packs to achieve the desired weight. The sustainment load configurations included the same load-carriage equipment as the approach loads plus additional plates for increased weight.

The masses carried in each study are presented in Table 2. They reflect the mass of clothing and all other items on the body. They were calculated by subtracting a participant's nude body mass from the mass of the participant wearing load-carriage equipment and the basic outfit for the biomechanics testing.

Procedure

The same tests were included in all four, original studies and identical procedures were followed in administering the tests. In each study, anthropometric measurements were taken on the participants and the participants carried out maximal performance, energy cost, biomechanics, grenade throw, and rifle marksmanship tests. The maximal performance tests, all of which were timed, included a 3.2-km run, a six-station obstacle course traversal, and two individual movement techniques (IMTs). For one IMT, the participant walked at normal marching speed and, after a verbal signal from the investigator, dropped to a prone position on the ground and then returned to a standing position. For the second IMT, the participant walked at normal marching speed and, after a verbal signal from the investigator, dropped to a prone position on the ground, rolled, and aimed the weapon.

This report includes the results of the 3.2-km course run, energy cost testing, and biomechanics testing only, because these tests were administered under all three load

configurations, whereas the other tests were administered under only one, the fighting load. For each of the tests, the order of the presentation of the load configurations and load-carriage systems was systematically balanced across volunteers to prevent bias in the results due to order effects.

Table 2
Means (and SDs) of Masses Carried (kg)

System	Load Configuration		
	Fighting	Approach	Sustainment
LW I	23.45	35.47	50.11
vs.	(0.89)	(2.39)	(2.71)
ALICE	14.66	23.41	37.54
	(0.72)	(0.73)	(1.02)
LW II	20.42	32.68	49.29
	(1.18)	(1.12)	(1.29)
MOLLE	13.05	26.84	40.16
vs.	(0.63)	(0.49)	(0.60)
ALICE	11.82	24.07	38.36
	(0.39)	(0.51)	(0.52)
MOLLE	12.87	26.18	40.51
vs.	(1.53)	(1.67)	(2.05)
MLS	12.26	24.18	37.65
	(1.58)	(1.75)	(1.76)

Maximal Performance

The time required to traverse a 3.2-km course on foot was measured. The course included several small hills and consisted of paved road, dirt road, field and wooded trails. The participants were instructed to traverse the course as quickly as possible without injuring themselves. Due to equipment problems, this test was not carried out in the LW II study. In the other studies, a participant completed one run of the course in each load configuration with each type of load-carriage equipment. There was a minimum of 24 hr between each run of the course.

Energy Cost

Energy cost was quantified by measuring oxygen uptake (O_2 uptake). For someone eating a normally balanced diet, rate of energy utilization during exercise is closely correlated with the rate of oxygen consumption. The equipment used to take the measurements was a custom-made system that consisted of an oxygen analyzer, a carbon dioxide analyzer, an airflow meter that emitted an electronic pulse for each 10 ml of air passing through it, an electronic pulse counter, and a Hewlett-Packard desktop computer and printer. The system also included a mouthpiece and flexible tubing, connecting the

participant to the system, that was supported by headgear and an overhead arm. The system analyzed and recorded the rate of oxygen consumption, in liters per minute ($L \cdot min^{-1}$) and in milliters per minute per kilogram body mass ($ml \cdot min^{-1} \cdot kg^{-1}$), every 30 s as the volunteer walked or ran on a treadmill.

In order to normalize energy cost to each participant's level of aerobic fitness, maximal oxygen uptake ($\dot{V}O_{2max}$) was measured prior to the start of formal testing in all studies except the one comparing the MOLLE and the MLS. A participant did not perform any other test-related activities on the day in which maximal oxygen uptake was measured. Maximal oxygen consumption testing began with the participant warming up by running for 5 min at 8 $km \cdot hr^{-1}$ on a level treadmill and then resting for 5 min. After the rest, the participant ran on the treadmill at a 5% grade and at a speed considered easy to moderate based on the participant's heart rate during the warm-up period. The treadmill speed was increased by 0.8 $km \cdot hr^{-1}$ every 2 min until the participant's oxygen consumption reached maximum. The maximum was defined as the point at which oxygen consumption increased by less than 2 $ml \cdot min^{-1} \cdot kg^{-1}$ of body mass in the 1 min following a speed increase. The participants wore underwear, socks, running shoes, shorts, and a T-shirt during the maximal oxygen uptake testing.

Oxygen consumption with the load-carriage equipment was measured as the participants walked at 4.8 $km \cdot hr^{-1}$ on a level treadmill. A participant had one trial in each load configuration with each type of load-carriage system. Each trial lasted approximately 5 min to allow the participant to reach a steady-state rate of oxygen consumption, and a rest of at least 5 min followed a trial. Oxygen consumption was measured during each 30-s interval of the last 1.5 min of testing, and a mean of the three measurements was obtained. Energy cost was expressed in two ways: as a percentage of the participant's $\dot{V}O_{2max}$ and as normalized by the participant's nude body mass.

Biomechanics

The effects of load configuration and load-carriage system on the biomechanics of walking gait were assessed through the simultaneous capture of body motions and ground reaction forces. In the biomechanics testing, a participant walked along a horizontal path, approximately 13 m long. A force plate (AMTI, Watertown, MA) was mounted flush with the floor toward the end of the path. Data capture from the force plate was triggered manually about one stride before the right heel struck the plate. Force plate output was recorded for approximately 3 s at 1000 Hz. A video motion analysis system with six cameras (Qualysis, Glastonbury, CT) was set up in the area of the force plate. Each camera was equipped with a ring of infrared LEDs. The cameras captured the infrared light reflected back from reflective markers placed on the participant and fed data to a desktop computer that calculated the three-dimensional position of the markers. The camera system operated at 60 Hz. A computer program normalized the results from all trials to one complete stride, centered on the force plate, with the time for the complete stride set equal to 100%.

For each trial, the participant walked at 4.8 $km \cdot hr^{-1}$ along the walkway. The participant was aided in maintaining the proper speed by a pacing device consisting of a striped cord, with alternating light and dark bands, moving at 4.8 $km \cdot hr^{-1}$ parallel to the walkway. In addition, an electronic device timed how long it took the participant to break an infra-red beam at the end of the filming area after breaking another one at the start of the filming area, inferring the participant's actual walking speed. The data from any trial in which the speed was not within $\pm$ 5% of 4.8 $km \cdot hr^{-1}$ (i.e., between 4.56 $km \cdot hr^{-1}$ and 5.04 $km \cdot hr^{-1}$) were discarded and the trial was repeated. For the first Land Warrior study (LW I vs. ALICE), nine trials were conducted with each load configuration and load-carriage system. For the second Land Warrior study (LW II), 18 trials were conducted. For the remaining two studies (MOLLE vs. ALICE and MOLLE vs. MLS), three trials were conducted with each load configuration and load-carriage system. The differences in the number of trials were due to changes in the way in which pressure data, which were recorded concurrently with the kinetic and kinematic data, were obtained.

For the biomechanics testing, spherical reflective markers, approximately 2.5 cm in diameter, were placed on the right side of the body at the following locations: the base of the fifth metatarsal; the lateral malleolus of the ankle; the lateral femoral condyle of the knee; the greater trochanter at the hip; the acromion process of the shoulder; the lateral epicondyle of the elbow; the radial styloid process of the wrist; and the zygomatic arch of the head. In addition, a marker was placed at the location of the sagittal plane center of mass (COM) of the load-carriage system. The reflective markers were attached to the skin, boot, and pack using double-sided foam tape. The location of the COM was determined by placing the ballistic protective vest and the loaded load-carriage system, including the load-bearing vest, on a lightweight, foam dummy torso and using a standard balance-board technique (Winter, 1979).

The recorded kinematic data were processed using the Qualysis software to produce a time series of three-dimensional coordinates for each reflective marker. The data for the left side of the body were generated by phase-shifting the data from the right side by 180 degrees, under the assumption of left-right symmetry of gait. This allowed the data to be analyzed using a 12-segment model of the body (two feet, two shanks, two thighs, trunk, two upper arms, two forearms and hands, and head). The segments were defined as follows:

Foot: the segment below the ankle marker
Shank: the segment between the ankle and the knee markers
Thigh: the segment between the knee and the hip markers
Trunk: the segment between the hip and the shoulder markers
Upper arm: the segment between the shoulder and the elbow markers
Forearm-and-hand: the segment between the elbow marker and the fingertips
Head: the segment between the midpoint of the shoulders, through the head marker, to the top of the head

The inertial properties of each segment were estimated using the methods given by Dempster (1955). A single stride from each trial was chosen for analysis. The stride

was centered on the force plate and was defined as the portion of the gait cycle from the time at which the right foot crossed in front of the left leg just prior to striking the force plate to the time at which the right foot next crossed in front of the left leg.

A custom computer program calculated various gait parameters for the stride centered on the force plate, based on the 12-segment kinematic model combined with the force plate data. The parameters of interest for this report are defined as follows:

Double-support duration (% of stride): The percentage of the stride in which both feet were in contact with the ground.

Stride frequency (strides·s^{-1}): The number of strides completed per second.

Sagittal plane segment angles: The minimum value, maximum value, and range over the entire stride were computed for each of four body angles. A graphical definition of each angle is presented in Figure 1. Only the trunk angle is directional; it was measured as positive when the trunk was inclined forward of the vertical and negative when the trunk was inclined backwards from the vertical. The other three angles are included angles and are, therefore, always positive and larger as the adjacent segments move further apart.

Ankle angle (deg): The ventral sagittal plane angle between the foot segment and the shank segment.

Knee angle (deg): The dorsal sagittal plane angle between the shank segment and the thigh segment.

Hip angle (deg): The ventral sagittal plane angle between the thigh segment and the trunk segment.

Trunk angle (deg): The sagittal plane angle measured from the vertical to the trunk segment. A positive angle indicates forward inclination of the trunk; a negative angle indicates backward inclination.

Body COM vertical position (cm): The vertical position of the body COM measured from the ground, calculated using the method described by Winter (1979). The minimum, maximum, and range of this variable over the entire stride were determined.

Ground reaction forces (GRFs):

Vertical force (N): The vertical force exerted by the ground on the foot.

Braking force (N): The horizontal force exerted by the ground on the foot in a direction opposite that of locomotion. By convention, this is expressed as a negative number.

Propulsive force (N): The horizontal force exerted by the ground on the foot in the direction of locomotion.

Medial force (N): The horizontal force exerted by the ground on the foot towards the midline of the body. By convention, medial force is expressed as a negative number.

Lateral force (N): The horizontal force exerted by the ground on the foot away from the midline of the body.

Joint reaction forces (N): The internal forces at the body joints (the ankle, the knee, and the hip). The maximum and the mean for these variables over the entire stride were calculated.

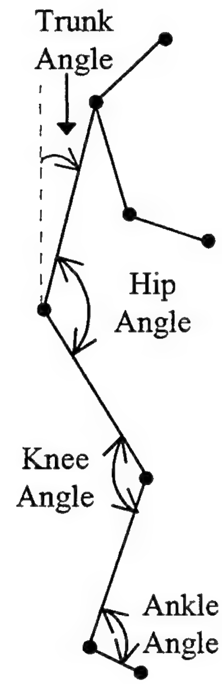

Figure 1. Definitions of ankle, knee, hip, and trunk angles used for biomechanical calculations.

Statistical Analyses

In each of the original studies, the results were analyzed using a one-way analysis of variance (ANOVA) for repeated measures to examine the effects of the load configuration and the load-carriage system design on the dependent variables. A p-value of less than .05 was considered indicative of a statistically significant difference. Where significant differences were found, the Duncan post-hoc test was used to determine which load configuration/system design combinations differed significantly from each other. Again, the significance level was set at $p < .05$. The results of these within-study analyses are presented in this report because they provide some information on the effects of weight carried, albeit on a study-by-study basis.

Results of analyses carried out on the pooled data from all four studies are also presented here. Analyses of the pooled data included calculation of Pearson product-moment correlation coefficients (r) to determine the relationships between weight carried and individual dependent variables. A low correlation value does not necessarily mean there is not a relationship between the load and a dependent variable. Rather, it may mean that the relationship is not strongly linear. In addition to calculation of the correlations, the method of least squares was applied to fit simple linear regression equations to the pooled data. Finally, the linear fits for some variables were tested for equal slopes. These tests were done using an ANOVA, with the significance level set at $p < .05$.

The raw data on which the correlation and regression analyses were done were the individual trials for each participant in each of the four, original studies. In the maximal performance and the energy cost testing, a participant performed one trial under each load configuration and load-carriage design combination. In the biomechanics testing, on the other hand, a participant performed from three to 18 trials under each combination of load configuration and load-carriage system design.

The independent measure used in the correlation and regression analyses performed on the maximal performance and the energy cost data was the weight of the load carried, which included the weight of the clothing and all other items worn or carried on the body (i.e., the "skin-out" weight). Load weight calculated in this same fashion was the independent measure used in the correlation and regression analyses performed on the temporal and the kinematic variables recorded in the biomechanics testing. For the variables from the biomechanics testing that involved forces, which are dependent in large part on total weight supported, body-plus-load weight was chosen as the independent variable. This was the weight of the body plus clothing and all other items worn and carried on the body.

Results

The results presented here include tables containing means and standard deviations for the load configuration/system design combinations tested in the individual studies that comprise this summary analysis. The four, original studies were analyzed separately using the ANOVA and, when appropriate, Duncan post-hoc tests were applied to identify significant differences among the load configuration/system design combinations tested in that study. In the tables, the data for the four studies are separated by horizontal lines. The superscripted letters associated with the means for a study indicate the findings from the analyses of that study. Means with different superscripts differed significantly ($p < .05$). In those instances in which the main effect was not significant, all means for a study are superscripted with the same letter. Also included in the results presented here are tables and figures containing the findings from correlation and regression analyses. These analyses were carried out on the pooled data from all four, original studies, as opposed to the data set from each individual study.

Maximal Performance

The means in Table 3 show that the time to traverse a 3.2-km course on foot as quickly as possible increased significantly in the original studies as the weight carried increased. The correlation and regression analyses, presented in Figure 2, provide more detailed information on the relationships between course completion time and weight carried. Three sets of analyses were done. For one, both the male and the female data were included. A moderately strong, positive relationship was obtained between course completion time and weight carried, $r(190) = +.56, p < .01$. About 30% of the variance in time to complete the 3.2-km course was accounted for by the weight. The data of the male and the female participants were also examined separately. These analyses yielded higher, positive correlations between course completion time and weight carried, Males: $r(123) = +.76, p < .01$; Females: $r(65) = +.73, p < .01$. From the slopes of the separate linear regression equations for the males and the females, it can be seen that the females evidenced a greater increase in completion time for a given increase in weight carried than the males did (Figure 2).

Energy Cost

The data in Table 4 are results from the energy cost testing expressed in two different ways. The first dependent measure listed is O_2 uptake expressed as a percentage of the $\dot{V}O_{2max}$ for each participant. These results from the original studies show that the participants used significantly higher percentages of their maximal oxygen consumption when carrying heavier loads. The second variable shown in Table 4 is the oxygen uptake relative to each participant's body mass. This measure normalizes the oxygen uptake to the individual's body size. Again, across all studies, the participants used progressively greater amounts of oxygen as the loads became heavier.

Table 3
Means (and SDs) of Time (min) to Traverse a 3.2-km Course on Foot

System	Load Configuration: Fighting	Approach	Sustainment
LW I	21.38^{C}	24.20^{B}	30.58^{A}
vs.	(2.16)	(2.54)	(3.89)
ALICE	19.47^{D}	21.64^{C}	25.32^{B}
	(2.17)	(2.74)	(2.78)
LW II[a]	—	—	—
MOLLE	26.89^{C}	31.35^{B}	39.96^{A}
vs.	(2.06)	(5.13)	(4.31)
ALICE	25.08^{C}	30.63^{B}	36.19^{A}
	(2.47)	(3.28)	(6.13)
MOLLE	21.01^{C}	25.58^{B}	29.40^{A}
vs.	(2.03)	(2.38)	(1.97)
MLS	21.30^{C}	25.26^{B}	29.63^{A}
	(1.78)	(1.84)	(2.35)

Note. Means that do not share the same superscript differed significantly ($p < .05$) on the Duncan post-hoc test from the other means between the same horizontal lines.
[a]Traversal of a 3.2-km course was not included in the LW II study.

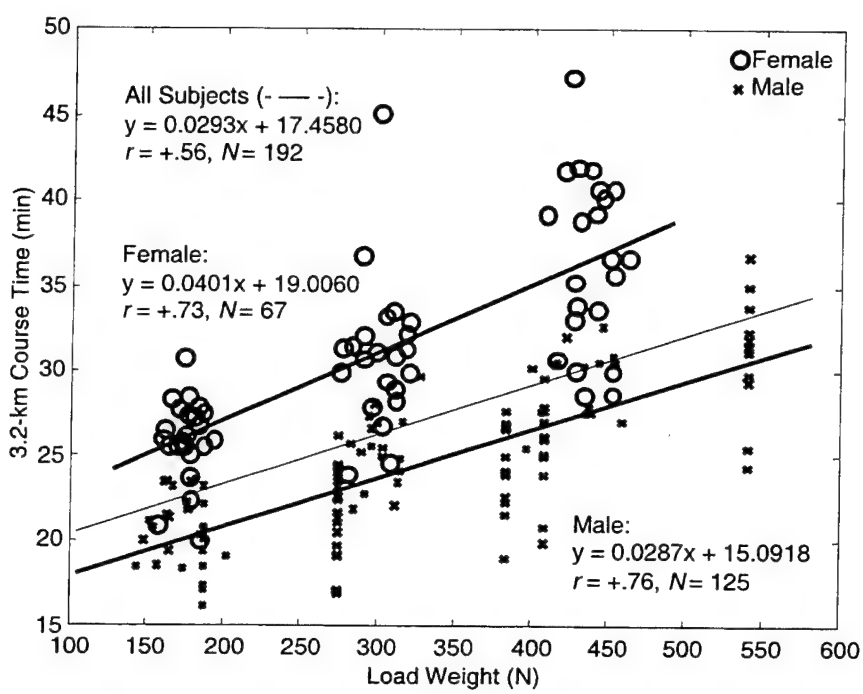

Figure 2. Scatter diagram and plot of simple linear regression equations for 3.2-km course time as a function of weight carried.

Table 4
Means (and SDs) of Oxygen Uptake While Carrying Various Loads at 4.8 km·hr^{-1}

	O_2 Uptake as Percentage of $\dot{V}O_{2max}$ (%)			O_2 Uptake Relative to Body Mass (ml·min^{-1}·kg^{-1})		
	Load Configuration			Load Configuration		
System	Fighting	Approach	Sustainment	Fighting	Approach	Sustainment
LW I	30.54^{C}	33.40^{B}	40.77^{A}	17.76^{C}	19.44^{B}	23.77^{A}
vs.	(3.04)	(2.73)	(5.13)	(1.63)	(1.66)	(3.12)
ALICE	29.97^{C}	30.94^{C}	34.68^{A}	17.43^{C}	17.99^{C}	20.17^{B}
	(2.36)	(2.73)	(3.64)	(1.25)	(1.36)	(2.04)
LW II	31.23^{C}	35.34^{B}	40.49^{A}	17.34^{C}	19.49^{B}	22.24^{A}
	(2.55)	(6.04)	(5.32)	(1.52)	(3.43)	(3.28)
MOLLE	37.25^{C}	41.88^{B}	50.37^{A}	18.05^{C}	20.29^{B}	24.34^{A}
vs.	(4.28)	(4.61)	(7.02)	(1.47)	(1.38)	(2.06)
ALICE	37.05^{C}	40.87^{B}	49.18^{A}	17.95^{C}	19.79^{B}	23.77^{A}
	(3.92)	(4.75)	(7.44)	(1.09)	(1.49)	(2.31)
MOLLE[a]	—	—	—	17.36^{C}	18.63^{B}	21.03^{A}
vs.				(1.74)	(1.96)	(2.56)
MLS[a]	—	—	—	17.39^{C}	18.68^{B}	20.71^{A}
				(1.99)	(2.04)	(2.92)

Note. For each dependent variable, means that do not share the same superscripts differed significantly ($p < .05$) on the Duncan post-hoc test from the other means between the same horizontal lines.
[a]Testing of $\dot{V}O_{2max}$ was not included in the MOLLE vs. MLS study.

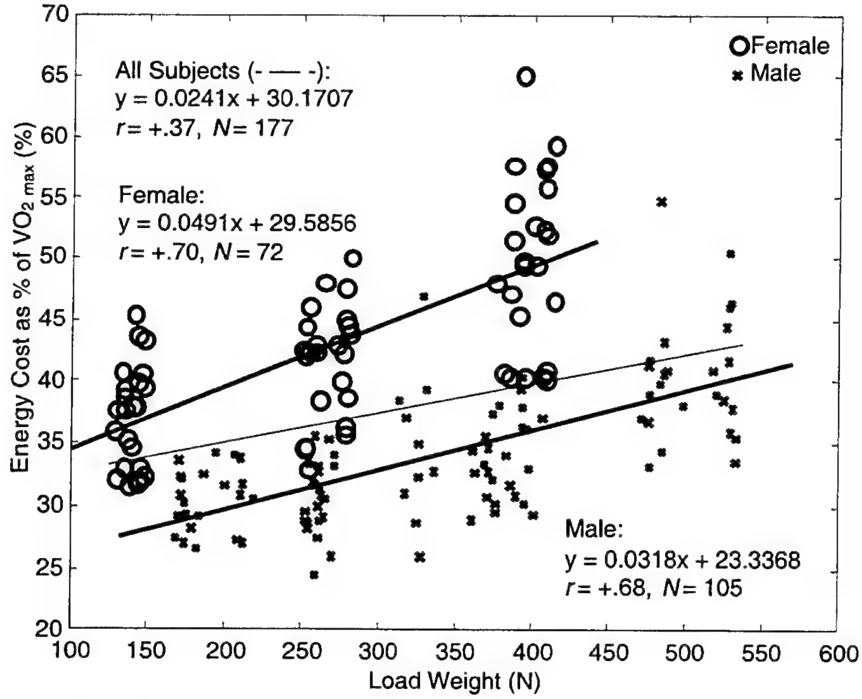

Figure 3. Scatter diagram and plot of simple linear regression equations for oxygen consumption normalized by maximal oxygen consumption as a function of weight carried.

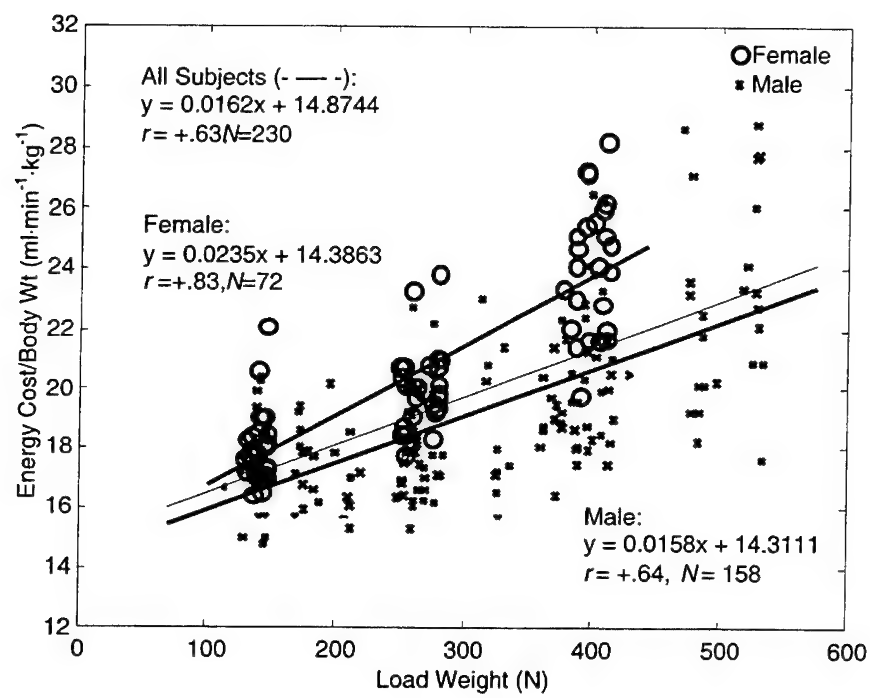

Figure 4. Scatter diagram and plot of simple linear regression equations for oxygen consumption normalized by body weight as a function of weight carried.

The results of the correlation and regression analyses performed on the energy cost measure of O_2 uptake as a percentage of $\dot{V}O_{2max}$ are presented in Figure 3. As was done for the 3.2-km course run, three sets of analyses were carried out on the dependent measure; the male and the female data were analyzed as a combined data set, as well as separately. For the combined data, O_2 uptake as a percentage of $\dot{V}O_{2max}$ had a low correlation with the weight carried, $r(175) = +.37, p < .01$. The separate analyses of this same measure yielded higher correlations for both the males, $r(103) = +.68, p < .01$, and the females, $r(70) = +.70, p < .01$. Comparison of the slopes of the linear regression equations for the males and the females reveals that the females used a greater percentage of their $\dot{V}O_{2max}$ for each increase in weight carried than the males did (Figure 3).

Correlation and regression analyses results for the second energy cost measure, O_2 uptake normalized by body weight, are presented in Figure 4. The combined male and female data yielded a moderate linear correlation between O_2 uptake and weight carried, $r(228) = +.63, p < .01$. In addition, when the data of the females were again looked at separately from that of the males, the correlation for the females revealed a stronger linear relationship between weight carried and O_2 uptake normalized by body weight than did the correlation for the males, Males: $r(156) = +.64, p < .01$; Females: $r(70) = +.83$, $p < .01$. About 41% of the variance in O_2 uptake for the males and 69% of the variance in O_2 uptake for the females were accounted for by the weight carried. Comparison of the slopes of the regression equations for the males and the females reveals that the increase in energy cost relative to body mass for a given increase in weight carried was greater for the females than for the males (Figure 4).

Biomechanics

The computer program used in the acquisition of the biomechanics data calculated over 200 dependent variables from the raw data. The variables chosen for treatment in this summary analysis included: variables analyzed in one or more of the four, original studies that yielded a significant effect of weight carried; variables related to those in the original studies that revealed significant effects of weight carried; and variables that previous research and experience indicated were likely to be affected by weight carried. These dependent measures can be divided into five categories. The categories are: temporal gait variables; sagittal plane body angle variables; body COM height variables; ground reaction force variables; and joint reaction force variables. Results pertaining to each of the categories of dependent measures are presented below. For all categories, except the ground and the joint reaction forces, the independent variable in the correlation and regression analyses was weight carried, which was the weight of all items worn or carried by the participant. For the correlation and regression analyses performed on the ground reaction force and the joint reaction force variables, the independent variable was body-plus-load weight, the weight of all items worn or carried, plus the participant's nude body weight.

Table 5
Means (and SDs) of Temporal Gait Variables

	Double-Support Duration (% of Stride) Load Configuration			Stride Frequency (Strides·s^{-1} x 10) Load Configuration		
System	Fighting	Approach	Sustainment	Fighting	Approach	Sustainment
LW I	13.93^{C}	14.50^{B}	15.33^{A}	8.60^{AB}	8.49^{C}	8.58^{AB}
vs.	(1.73)	(1.36)	(1.47)	(0.47)	(0.46)	(0.41)
ALICE	13.27^{D}	14.00^{C}	14.78^{B}	8.65^{A}	8.60^{AB}	8.53^{BC}
	(1.77)	(1.51)	(1.54)	(0.33)	(0.39)	(0.44)
LW II	13.74^{C}	14.73^{B}	15.39^{A}	8.47^{A}	8.47^{A}	8.45^{A}
	(1.22)	(1.18)	(1.22)	(0.30)	(0.42)	(0.30)
MOLLE	13.51^{C}	15.53^{AB}	16.79^{A}	9.30^{A}	9.35^{A}	9.47^{A}
vs.	(2.41)	(3.16)	(3.07)	(0.57)	(0.70)	(0.52)
ALICE	14.00^{C}	14.53^{BC}	16.30^{A}	9.48^{A}	9.45^{A}	9.42^{A}
	(3.80)	(2.06)	(3.02)	(0.87)	(0.60)	(0.76)
MOLLE	13.25^{BC}	13.72^{B}	14.58^{A}	8.59^{A}	8.43^{B}	8.51^{AB}
vs.	(2.33)	(1.73)	(1.44)	(0.47)	(0.43)	(0.41)
MLS	12.81^{C}	13.70^{B}	14.88^{A}	8.45^{AB}	8.44^{AB}	8.51^{AB}
	(1.15)	(1.44)	(1.48)	(0.41)	(0.43)	(0.33)

Note. For each dependent variable, means that do not share the same superscripts differed significantly ($p < .05$) on the Duncan post-hoc test from the other means between the same horizontal lines.

Temporal Gait Variables

Table 5 contains the means from each original study for two temporal gait variables, double-support duration and stride frequency. It can be seen that increases in weight carried were associated with significant increases in the percentage of a stride spent in the double-support phase. Stride frequency, however, did not change consistently with changes in the weight carried, and two of the original studies did not yield significant differences among weights carried (Table 5). Findings from the correlation and regression analyses of the two temporal gait variables are presented in Figures 5 and 6. There was a low, positive correlation between double-support duration and weight carried, $r(1560) = +.37, p < .01$, which indicated that approximately 14% of the variance in double-support duration was attributable to the weight carried (Figure 5). The correlation between stride frequency and weight carried was lower and negative, $r(1565) = -.14, p < .01$, reflecting a slight, almost negligible, relationship (Figure 6).

Sagittal Plane Body Angle Variables

The means from the four, original studies for variables related to ankle, knee, hip, and trunk angles in the sagittal plane are presented in Tables 6 through 9, respectively. For each body angle, means are shown for the minimum, the maximum, and the range of the angle over one walking stride. Table 10 lists the correlation coefficients and the linear regression equations for these same body angle variables.

Ankle angle. The means in Table 6 indicate that there were significant effects of the weight carried on the ankle angle variables. The minimum angles tended to be smaller at the heavier loads, which reflects greater dorsiflexion of the foot at the ankle. The maximum angles tended to be larger at the heavier loads, reflecting greater plantarflexion of the foot. In consonance with these trends, the range of ankle movement was somewhat greater at the heavier loads. The correlations for the minimum and the maximum ankle angles were low, indicating that the linear relationships of these variables to the weight carried were weak (Table 10). The correlation of range of ankle angle with weight carried was somewhat higher; there was a small, but definite, positive relationship, with approximately 5% of the variance in range of ankle movement being attributable to weight carried.

Knee angle. The means from the original studies, presented in Table 7, reveal that significant differences among the weights carried were obtained for the three knee angle variables. There was a tendency for minimum knee angle to increase and maximum knee angle to decrease with increases in the weight carried. These findings reflect decreased knee flexion at the heavier loads. Also, the range of movement about the knee was less with heavier than with lighter loads. The correlations for the minimum and the maximum knee angles were low, indicating essentially negligible relationships of these variables with weight carried (Table 10). As was the case with the range of ankle angle, the correlation of range of knee angle with weight carried was small. It was also negative, indicating that range of movement at the knee decreased as load weight increased (Table 10). About 5% of the variance in range of knee movement was attributable to the weight carried.

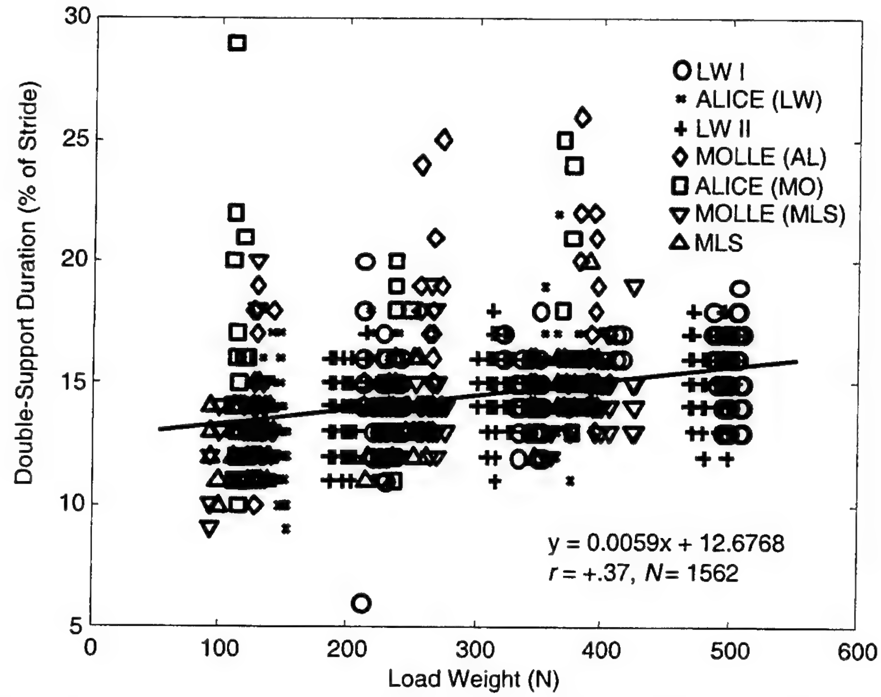

Figure 5. Scatter diagram and plot of simple linear regression equation for double-support duration as a function of weight carried.

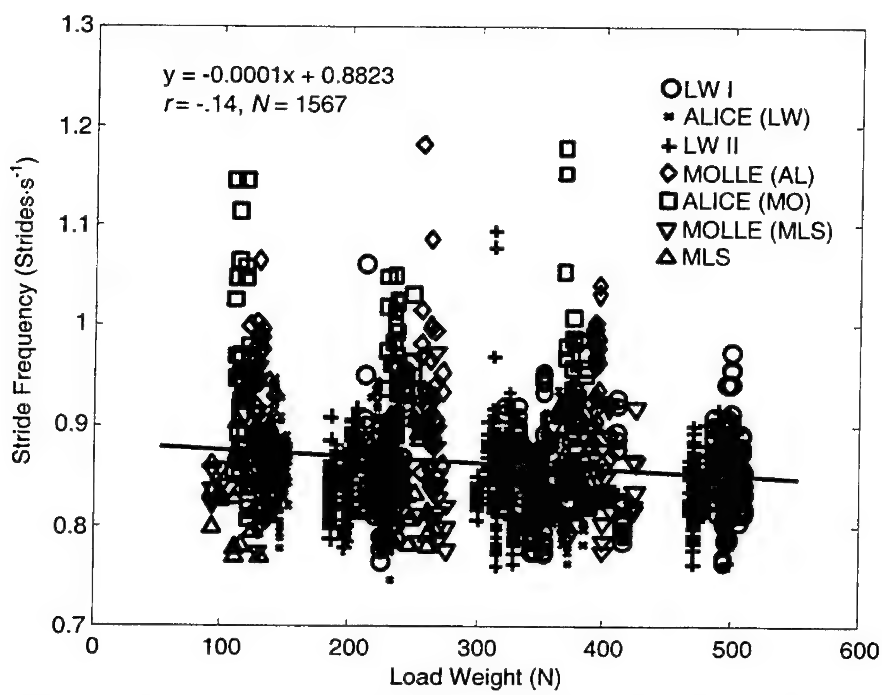

Figure 6. Scatter diagram and plot of simple linear regression equation for stride frequency as a function of weight carried.

Table 6
Means (and SDs) of Sagittal Plane Ankle Angle Variables (deg)

	Minimum Angle Load Configuration			Maximum Angle Load Configuration			Range of Angle Load Configuration		
System	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.
LW I	104.95^{A}	102.77^{C}	103.98^{B}	138.06^{B}	137.60^{B}	139.53^{A}	33.10^{D}	34.83^{B}	35.55^{A}
vs.	(3.47)	(3.57)	(4.24)	(5.35)	(4.85)	(5.84)	(4.03)	(4.32)	(4.33)
ALICE	103.59^{B}	104.21^{AB}	104.87^{A}	136.38^{C}	137.44^{B}	138.87^{A}	32.80^{D}	33.23^{D}	34.00^{C}
	(3.97)	(3.26)	(4.56)	(5.15)	(5.15)	(6.39)	(4.49)	(4.06)	(4.33)
LW II	104.24^{A}	103.71^{B}	103.83^{AB}	136.67^{C}	137.41^{B}	138.00^{A}	32.43^{C}	33.70^{B}	34.17^{A}
	(5.75)	(5.89)	(5.13)	(5.59)	(5.91)	(5.85)	(3.05)	(2.95)	(4.22)
MOLLE	105.38^{A}	104.27^{AB}	104.03^{AB}	138.08^{AB}	138.64^{A}	138.50^{AB}	32.70^{B}	34.37^{A}	34.47^{A}
vs.	(5.82)	(6.88)	(7.29)	(7.26)	(8.10)	(8.13)	(3.97)	(4.31)	(4.16)
ALICE	105.35^{A}	105.63^{A}	103.30^{B}	137.52^{B}	137.78^{AB}	138.67^{A}	32.17^{B}	32.15^{B}	35.37^{A}
	(6.45)	(6.98)	(9.65)	(7.44)	(8.61)	(7.93)	(4.52)	(5.14)	(6.97)
MOLLE	102.43^{B}	102.08^{B}	100.63^{C}	132.91^{C}	134.38^{AB}	134.33^{AB}	30.48^{D}	32.30^{BC}	33.70^{A}
vs.	(6.70)	(6.90)	(6.86)	(6.27)	(6.29)	(6.23)	(3.41)	(3.57)	(3.75)
MLS	103.74^{A}	101.67^{BC}	101.60^{BC}	134.18^{AB}	133.51^{BC}	134.83^{A}	30.44^{D}	31.84^{C}	33.22^{AB}
	(6.31)	(6.34)	(6.35)	(5.50)	(6.38)	(5.77)	(3.24)	(2.63)	(2.99)

Note. For each dependent variable, means that do not share the same superscripts differed significantly ($p < .05$) on the Duncan post-hoc test from the other means between the same horizontal lines.

Table 7
Means (and SDs) of Sagittal Plane Knee Angle Variables (deg)

	Minimum Angle Load Configuration			Maximum Angle Load Configuration			Range of Angle Load Configuration		
System	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.
LW I	108.24^{E}	109.97^{B}	111.05^{A}	176.27^{C}	176.17^{C}	174.39^{D}	68.02^{A}	66.20^{B}	63.35^{D}
vs.	(4.25)	(4.30)	(4.70)	(4.77)	(4.62)	(3.96)	(3.93)	(4.18)	(4.41)
ALICE	109.23^{CD}	109.06^{D}	109.69^{BC}	177.65^{A}	176.89^{B}	174.47^{D}	68.42^{A}	67.82^{A}	64.78^{C}
	(4.30)	(4.66)	(4.56)	(4.43)	(4.67)	(4.92)	(4.38)	(4.02)	(4.81)
LW II	111.19^{B}	111.86^{A}	111.84^{A}	181.13^{A}	179.31^{B}	178.82^{B}	69.94^{A}	67.45^{B}	66.98^{B}
	(4.34)	(5.27)	(5.23)	(5.98)	(7.09)	(7.30)	(5.57)	(6.47)	(6.53)
MOLLE	107.42^{ABC}	106.43^{C}	108.43^{A}	175.25^{AB}	175.05^{AB}	175.71^{A}	67.83^{A}	68.62^{A}	67.28^{A}
vs.	(5.32)	(5.68)	(6.92)	(7.96)	(7.99)	(8.21)	(7.04)	(7.44)	(7.74)
ALICE	106.79^{BC}	107.38^{ABC}	108.04^{AB}	170.23^{B}	175.16^{AB}	171.54^{AB}	63.43^{A}	67.78^{A}	63.50^{A}
	(5.62)	(5.49)	(6.93)	(16.99)	(7.37)	(14.14)	(18.49)	(6.73)	(15.29)
MOLLE	109.37^{AB}	109.92^{A}	110.02^{A}	181.87^{A}	181.04^{A}	179.96^{B}	72.50^{A}	71.11^{B}	69.95^{BC}
vs.	(5.49)	(5.89)	(5.99)	(8.73)	(7.31)	(7.82)	(6.78)	(6.54)	(5.72)
MLS	108.50^{B}	108.51^{B}	109.26^{AB}	182.09^{A}	179.24^{BC}	178.81^{C}	73.59^{A}	70.73^{BC}	69.55^{C}
	(5.82)	(4.82)	(6.36)	(8.21)	(6.57)	(8.16)	(6.68)	(5.87)	(6.51)

Note. For each dependent variable, means that do not share the same superscripts differed significantly ($p < .05$) on the Duncan post-hoc test from the other means between the same horizontal lines.

Table 8
Means (and SDs) of Sagittal Plane Hip Angle Variables (deg)

	Minimum Angle Load Configuration			**Maximum Angle** Load Configuration			**Range of Angle** Load Configuration		
System	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.
LW I	148.31^{B}	142.02^{C}	132.84^{E}	196.53^{B}	192.28^{C}	185.71^{E}	48.22^{C}	50.26^{B}	52.88^{A}
vs.	(5.48)	(5.70)	(6.20)	(3.76)	(5.14)	(6.46)	(3.53)	(4.09)	(4.49)
ALICE	152.17^{A}	147.75^{B}	137.60^{D}	197.80^{A}	196.05^{B}	188.08^{D}	45.63^{D}	48.30^{C}	50.47^{B}
	(5.25)	(5.32)	(7.48)	(4.29)	(4.73)	(6.42)	(3.19)	(3.57)	(5.05)
LW II	149.11^{A}	140.59^{B}	134.90C^{C}	198.64^{A}	193.71^{B}	189.60^{C}	49.54^{C}	53.12^{B}	54.70^{A}
	(3.74)	(5.76)	(5.63)	(4.96)	(6.39)	(7.16)	(3.29)	(4.73)	(4.68)
MOLLE	151.94^{A}	141.66^{C}	138.14^{D}	203.16^{A}	198.12^{C}	196.13^{D}	51.23^{D}	56.46^{C}	57.99^{B}
vs.	(5.70)	(5.85)	(6.28)	(6.93)	(6.72)	(7.65)	(2.91)	(3.78)	(3.77)
ALICE	150.75^{B}	142.48^{C}	135.66^{E}	201.74^{B}	198.08^{C}	194.13^{E}	50.99^{D}	55.60^{C}	59.47^{A}
	(6.83)	(5.86)	(6.10)	(7.48)	(7.40)	(7.33)	(3.37)	(4.60)	(3.46)
MOLLE	148.46^{A}	140.44^{B}	134.90^{D}	197.60^{A}	193.44^{B}	190.85^{CD}	49.14^{D}	53.01^{C}	55.95^{B}
vs.	(6.49)	(6.33)	(7.79)	(6.98)	(7.46)	(6.99)	(2.99)	(2.47)	(2.74)
MLS	147.65^{A}	138.37^{C}	133.24^{E}	197.34^{A}	191.88^{C}	190.48^{D}	49.69^{D}	53.51^{C}	57.24^{A}
	(6.81)	(5.84)	(7.03)	(8.43)	(7.12)	(7.58)	(2.62)	(2.95)	(3.35)

Note. For each dependent variable, means that do not share the same superscripts differed significantly ($p < .05$) on the Duncan post-hoc test from the other means between the same horizontal lines.

Table 9
Means (and SDs) of Sagittal Plane Trunk Angle Variables (deg)

	Minimum Angle Load Configuration			**Maximum Angle** Load Configuration			**Range of Angle** Load Configuration		
System	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.
LW I	-0.86^{E}	5.76^{C}	13.75^{A}	1.62^{E}	8.42^{C}	16.78^{A}	2.48^{D}	2.65^{C}	3.03^{B}
vs.	(2.61)	(3.05)	(4.04)	(2.48)	(3.07)	(4.19)	(0.78)	(0.68)	(0.91)
ALICE	-3.22^{F}	0.19^{D}	8.99^{B}	-0.67^{F}	3.13^{D}	12.26^{B}	2.55^{CD}	2.94^{B}	3.27^{A}
	(2.58)	(3.05)	(4.67)	(2.70)	(3.03)	(4.36)	(0.52)	(0.68)	(0.62)
LW II	0.26^{C}	7.21^{B}	12.11^{A}	2.66^{C}	10.22^{B}	15.52^{A}	2.40^{C}	3.01^{B}	3.46^{A}
	(2.67)	(2.81)	(3.42)	(2.68)	(2.69)	(3.41)	(0.65)	(0.77)	(1.03)
MOLLE	-5.16^{E}	2.75^{C}	5.70^{B}	-2.44^{E}	6.00^{C}	9.57^{B}	2.72^{D}	3.25^{C}	3.86^{AB}
vs.	(3.65)	(2.87)	(3.42)	(3.68)	(3.08)	(3.42)	(0.76)	(0.92)	(0.90)
ALICE	-4.21^{D}	2.42^{C}	8.13^{A}	-1.44^{D}	5.99^{C}	12.26^{A}	2.78^{D}	3.57^{BC}	4.13^{A}
	(4.79)	(3.54)	(3.55)	(4.60)	(3.62)	(3.85)	(1.09)	(0.73)	(1.06)
MOLLE	-0.38^{D}	6.73^{C}	10.99^{A}	1.79^{C}	9.33^{B}	13.78^{A}	2.17^{D}	2.60^{BC}	2.79^{B}
vs.	(4.04)	(4.83)	(4.66)	(4.11)	(4.92)	(4.56)	(0.76)	(0.61)	(0.82)
MLS	-0.18^{D}	6.92^{C}	10.07^{B}	2.29^{C}	9.61^{B}	13.94^{A}	2.47^{C}	2.69^{BC}	3.87^{A}
	(4.78)	(4.74)	(4.63)	(4.88)	(4.37)	(4.62)	(0.81)	(0.58)	(0.54)

Note. For each dependent variable, means that do not share the same superscripts differed significantly ($p < .05$) on the Duncan post-hoc test from the other means between the same horizontal lines.

Hip angle. Table 8 contains the means from the original studies for the hip angle variables. The minimum and the maximum hip angles decreased with increases in load weight. Also, the range of hip angle increased with weight carried. The correlations for minimum and maximum hip angle indicate that there were substantial, negative relationships of these two variables with weight carried (Table 10). About 46% of the variance in minimum hip angle and 27% of the variance in the maximum angle were attributable to the load carried. The correlation between range of hip angle and weight carried was relatively low, with about 14% of the variance in range of movement about the hip being accounted for by load weight (Table 10).

Trunk angle. The means from the original studies for the trunk angle variables, which are presented in Table 9, reveal that the minimum and the maximum angles increased with the weight carried. This relationship is also reflected in the correlations of weight carried with minimum and with maximum trunk angles (Table 10). Both correlations were positive. They were also high, indicating a substantial relationship between minimum and maximum trunk angles and weight carried. Approximately 65% of the variance in these trunk angle measures was attributable to the weight carried (Minimum trunk angle: $r^2 = .64$; Maximum trunk angle: $r^2 = .67$). The linear regression equations for minimum and for maximum trunk angle are presented graphically in Figures 7 and 8, respectively. Based upon the slopes of the regression equations (Figures 7 and 8), a 1-N increase in weight carried was associated with an increase in trunk lean of about 0.05 degrees. As was found for the minimum and the maximum angles, the means for range of trunk movement also generally increased with increases in the load carried (Table 9). However, the correlation between range of trunk movement and weight carried was relatively low, $r(1561) = +.33$, $p > .01$, with weight carried accounting for only about 11% of the variance in trunk range of movement (Table 10).

Body COM Height Variables

The means from the original studies for three variables related to the vertical position of the body's COM during gait are presented in Table 11. Analyses of the data from the original studies yielded significant differences among loads for each of the variables. Both the minimum and the maximum heights of the COM were significantly lower with heavier loads, although, in some studies, the difference was significant only between the lightest and heaviest loads. Changes in weight carried did not have consistent effects on the range of the vertical position of the body's COM (Table 11).

Table 12 contains the results for the simple correlation and linear regression analyses between the COM variables and weight carried. For these analyses, both the minimum and the maximum COM heights were divided by the participant's height. This normalization was done to eliminate differences among participants' data attributable to differences in body height. The linear regression results reinforce the ANOVA results. There was a definite tendency for both the minimum and the maximum COM heights to decrease with weight carried, $r(1565) = -.24$, $p < .01$ for minimum and for maximum COM heights, but load weight had little effect on the range of COM heights, $r(1564) = +.04$, $p > .05$.

Table 10
Correlation Coefficients and Simple Linear Regression Equations for Sagittal Plane Body Angle Variables (y), in Degrees, as Functions of Weight Carried (x), in Newtons

Variable	r^a	Regression Equation
	Ankle Angle	
Minimum	-.03	y = -0.0015x + 104.2880
Maximum	+.13*	y = 0.0066x + 135.3138
Range	+.23*	y = 0.0081x + 31.0258
	Knee Angle	
Minimum	+.14*	y = 0.0063x + 108.0867
Maximum	-.09*	y = -0.0051x + 179.3202
Range	-.23*	y = -0.0114x + 71.2509
	Hip Angle	
Minimum	-.68*	y = -0.0489x + 157.0760
Maximum	-.52*	y = -0.0327x + 203.8704
Range	+.38*	y = 0.0162x + 46.7944
	Trunk Angle	
Minimum	+.80*	y = 0.0442x - 8.4423
Maximum	+.82*	y = 0.0467x - 6.2410
Range	+.33*	y = 0.0025x + 2.1884

[a] *df* = 1565 for all variables, except maximum knee angle and range of knee angle, where *df* = 1560, and maximum trunk angle and range of trunk angle, where *df* = 1561.
*$p < .01$.

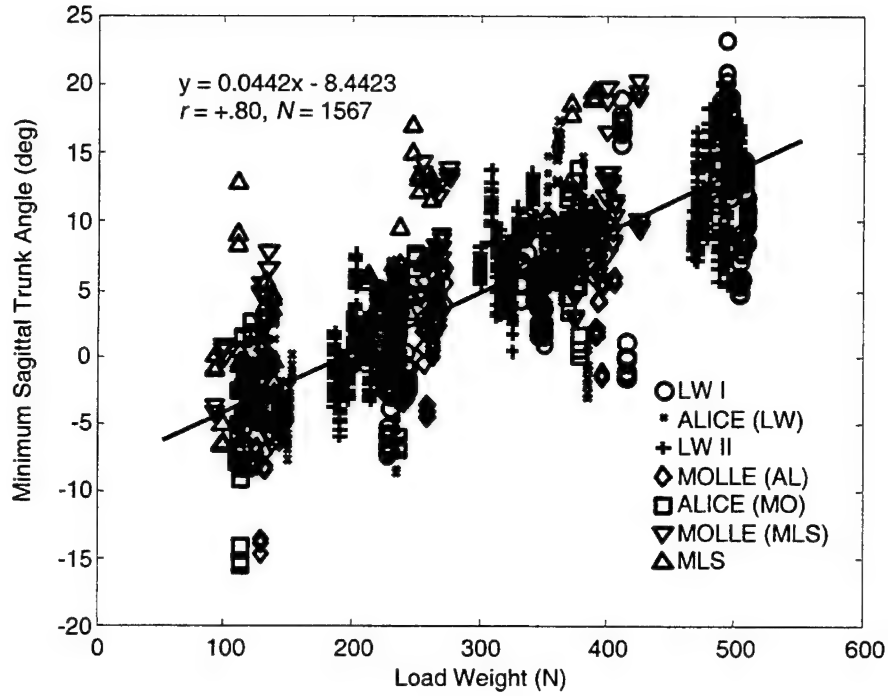

Figure 7. Scatter diagram and plot of simple linear regression equation of minimum sagittal trunk angle as a function of weight carried.

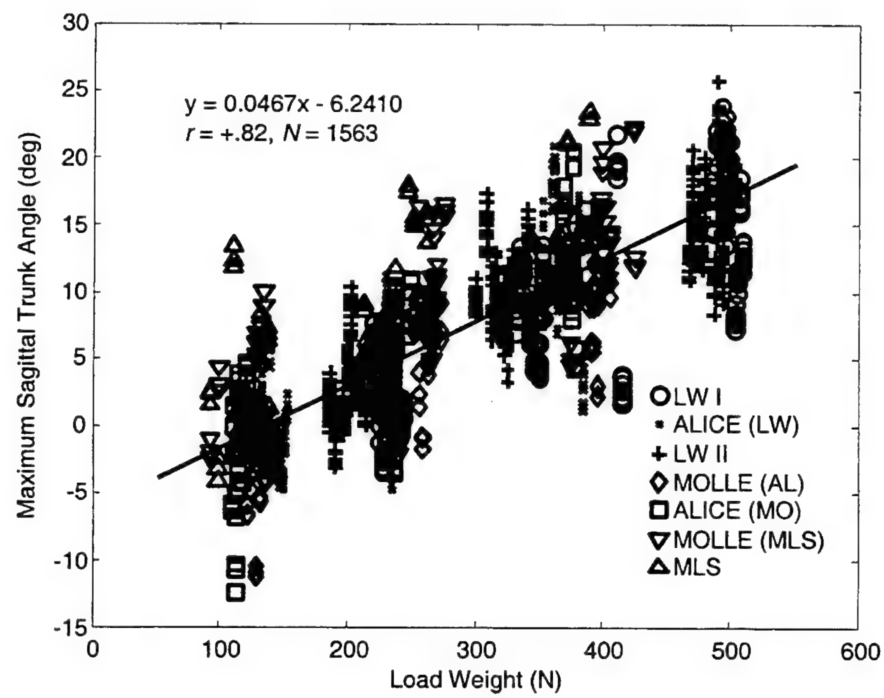

Figure 8. Scatter diagram and plot of simple linear regression equation of maximum sagittal trunk angle as a function of weight carried.

Table 11
Means (and SDs) of Body Center of Mass Height Variables (cm)

	Minimum Height Load Configuration			**Maximum Height** Load Configuration			**Range of Height** Load Configuration		
System	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.
LW I	96.98^{B}	96.30^{C}	95.07^{D}	102.41^{B}	101.79^{C}	100.42^{E}	5.44^{AB}	5.50^{A}	5.36^{BC}
vs.	(3.27)	(3.28)	(3.50)	(3.05)	(3.10)	(3.23)	(0.51)	(0.45)	(0.55)
ALICE	97.13^{AB}	97.30^{A}	96.21^{C}	102.52^{AB}	102.62^{A}	101.52^{D}	5.39^{BC}	5.33^{BC}	5.31^{C}
	(3.38)	(3.53)	(3.76)	(3.18)	(3.32)	(3.46)	(0.45)	(0.47)	(0.63)
LW II	96.51^{A}	95.13^{B}	94.11^{C}	102.10^{A}	100.79^{B}	99.86^{C}	5.60^{B}	5.66^{B}	5.76^{A}
	(2.92)	(2.91)	(2.94)	(2.86)	(2.88)	(2.89)	(0.60)	(0.85)	(0.80)
MOLLE	89.02^{A}	88.01^{D}	87.18^{F}	94.07^{A}	93.21^{C}	92.53^{E}	5.22^{AB}	5.20^{AB}	5.34^{A}
vs.	(4.08)	(4.27)	(3.97)	(4.27)	(4.50)	(4.13)	(0.55)	(0.50)	(0.60)
ALICE	88.83^{B}	88.51^{C}	87.61^{E}	93.91^{AB}	93.73^{B}	92.96^{D}	5.09^{B}	5.23^{AB}	5.36^{A}
	(3.98)	(3.84)	(4.14)	(4.11)	(3.96)	(4.44)	(0.64)	(0.58)	(0.82)
MOLLE	95.78^{A}	95.49^{AB}	94.48^{C}	101.82^{A}	101.34^{B}	100.82^{C}	6.03^{BC}	5.87^{C}	6.34^{A}
vs.	(3.32)	(2.76)	(2.84)	(3.21)	(2.94)	(2.97)	(0.81)	(0.68)	(0.94)
MLS	95.72^{A}	95.28^{B}	94.61^{C}	101.85^{A}	101.62^{AB}	100.77^{C}	6.13^{AB}	6.34^{A}	6.16^{AB}
	(3.37)	(3.35)	(3.06)	(3.58)	(3.27)	(3.00)	(0.69)	(0.82)	(0.93)

Note. For each dependent variable, means that do not share the same superscripts differed significantly ($p < .05$) on the Duncan post-hoc test from the other means between the same horizontal lines.

Table 12
Correlation Coefficients and Simple Linear Regression Equations for Body Center of Mass Height Variables (y) as Functions of Weight Carried (x), in Newtons

Variable[a]	r^{b}	Regression Equation
Minimum Height	-.24*	$y = -(0.23\times10^{-4})x + 0.5501$
Maximum Height	-.24*	$y = -(0.22\times10^{-4})x + 0.5817$
Range of Height	+.04	$y = (0.26\times10^{-5})x + 0.0549$

[a]The minimum and the maximum were calculated as COM height/body height. Range is expressed in meters.
[b]$df = 1565$ for all variables, except range of COM height, where $df = 1564$.
*$p < .01$.

Ground Reaction Force Variables

A number of GRF variables, selected from the force-time histories over a stride, were included as dependent measures in this summary analysis. Among them are the peak forces at initial contact of the foot with the ground and later in the stride cycle at the point when the foot was pushing off from the ground. Also included are GRFs averaged over a stride and impulses measured over a full stride. Data pertaining to these GRF variables are presented below. Body-plus-load weight was used as the independent variable in the correlation and regression analyses performed on these data.

Peak GRFs at heel-strike. Table 13 contains the means from the four, original studies for the peak vertical and the peak braking forces occurring when the foot contacted the force plate at heel-strike. Both peak forces increased significantly with load weight. In addition, correlation analyses of these forces at heel-strike yielded strong relationships with body-plus-load weight, Vertical GRF: $r(1565) = +.94, p < .01$; Braking GRF: $r(1565) = -.71, p < .01$. The correlation between braking force and body-plus-load weight was negative due to the convention of reporting braking force as negative. The correlations revealed that about 88% of the variance in peak vertical force and 50% of the variance in peak braking force at heel-strike were attributable to body-plus-load weight.

A plot of the simple linear regression equation for peak vertical force at heel-strike is presented in Figure 9. There was slightly less than a 1-N increase in the peak vertical force for each 1-N increase in body-plus-load weight. A similar plot for peak braking force at heel-strike is presented in Figure 10. The slope for the regression equation for the peak braking force is not as steep as that for the peak vertical force. For a 1-N increase in body-plus-load weight, there was a 0.18-N increase in peak braking force.

Peak GRFs at push-off. Means from the original studies for the peak vertical and the peak propulsive forces at push-off are presented in Table 14. As was the case with the peak heel-strike GRFs, the peak push-off GRFs increased significantly with increases in weight. Furthermore, as was also the case with the peak heel-strike GRFs, peak vertical and peak propulsive forces at push-off were highly and positively correlated with body-plus-load weight, Vertical GRF: $r(1565) = +.95, p < .01$; Propulsive GRF: $r(1565) = +.76, p < .01$. About 90% of the variance in peak vertical GRF at push-off and 58% of the variance in peak propulsive GRF at push-off were attributable to body-plus-load weight.

The linear regression equation for peak vertical GRF at push-off is presented graphically in Figure 11. The slope for the regression line indicates that the relationship between the peak vertical GRF at push-off and the body-plus-load weight was close to 1.0. The regression equation for peak propulsive GRF at push-off is plotted in Figure 12. The slope of the regression equation for this variable shows that there was an increase of only about 0.17 N in peak propulsive force for each 1-N increase in body-plus-load weight.

Table 13
Means (and SDs) of Peak Ground Reaction Forces at Heel-Strike (N)

	Vertical GRF Load Configuration			**Braking GRF** Load Configuration		
System	Fighting	Approach	Sustainment	Fighting	Approach	Sustainment
LW I	1032.64^{D}	1137.47^{C}	1299.61^{A}	-174.95^{B}	-202.03^{C}	-242.89^{E}
vs.	(133.20)	(115.53)	(110.30)	(28.42)	(27.66)	(32.98)
ALICE	951.24^{E}	1027.12^{D}	1183.16^{B}	-158.31^{A}	-178.15^{B}	-224.91^{D}
	(112.33)	(137.38)	(129.12)	(26.07)	(31.68)	(39.96)
LW II	1039.78^{C}	1141.53^{B}	1306.44^{A}	-175.16^{A}	-199.32^{B}	-239.64^{C}
	(150.65)	(139.91)	(117.61)	(34.20)	(40.58)	(38.34)
MOLLE	811.58^{D}	955.83^{B}	1075.62^{A}	-146.85^{A}	-184.14^{B}	-218.55^{C}
vs.	(84.20)	(78.26)	(96.21)	(19.84)	(25.02)	(27.95)
ALICE	802.96^{D}	931.78^{C}	1058.48^{A}	-139.65^{A}	-176.68^{B}	-214.87^{C}
	(82.83)	(87.59)	(84.45)	(23.74)	(29.67)	(33.46)
MOLLE	1089.63^{E}	1197.54^{C}	1352.59^{A}	-207.96^{A}	-227.46^{B}	-271.12^{C}
vs.	(149.84)	(145.98)	(141.99)	(44.30)	(39.49)	(48.45)
MLS	1081.75^{E}	1159.00^{D}	1300.28^{B}	-203.71^{A}	-227.14^{B}	-267.79^{C}
	(147.05)	(141.84)	(146.16)	(39.26)	(37.27)	(53.09)

Note. For each dependent variable, means that do not share the same superscripts differed significantly ($p < .05$) on the Duncan post-hoc test from the other means between the same horizontal lines.

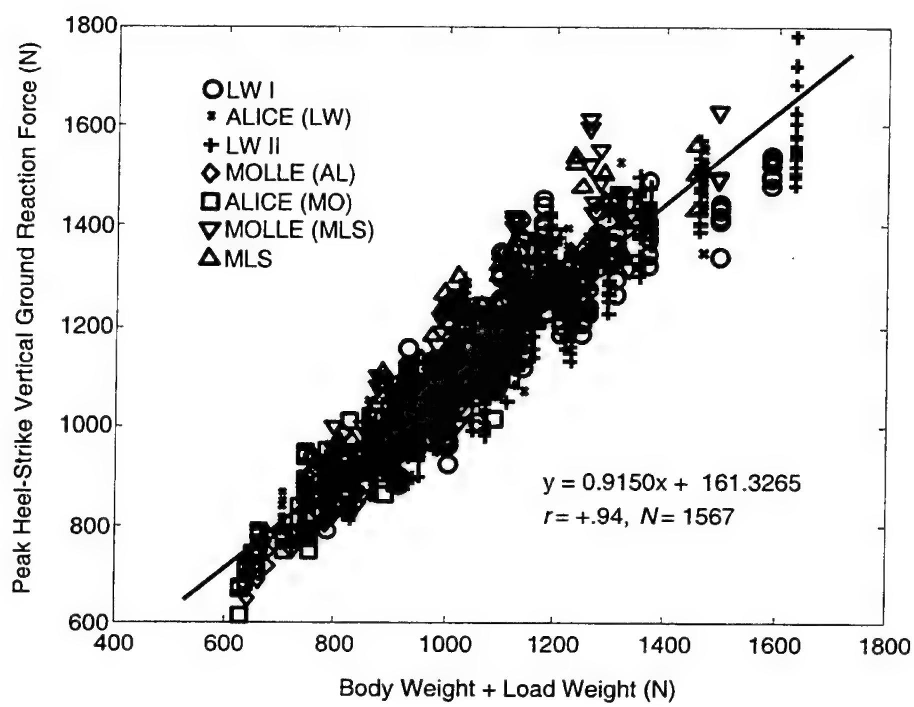

Figure 9. Scatter diagram and plot of simple linear regression equation for peak vertical ground reaction force at heel-strike as a function of body-plus-load weight.

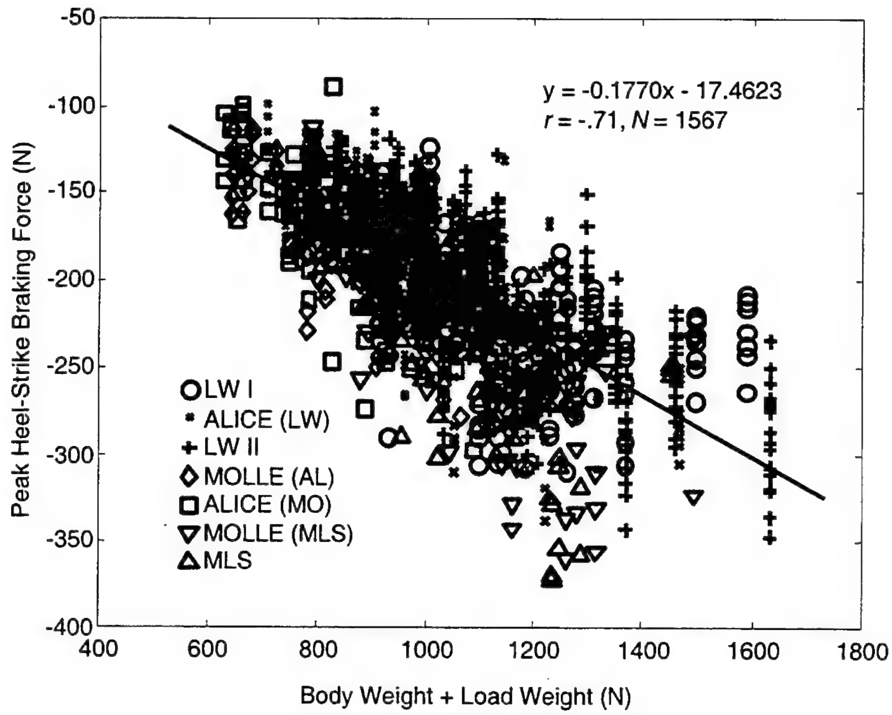

Figure 10. Scatter diagram and plot of simple linear regression equation for peak braking ground reaction force at heel-strike as a function of body-plus-load weight.

Table 14
Means (and SDs) of Peak Ground Reaction Forces at Push-Off (N)

	Vertical GRF Load Configuration			**Propulsive GRF** Load Configuration		
System	Fighting	Approach	Sustainment	Fighting	Approach	Sustainment
LW I	1035.47^{C}	1162.58^{B}	1283.76^{A}	176.72^{C}	193.92^{B}	214.41^{A}
vs.	(140.02)	(139.76)	(146.78)	(30.79)	(31.16)	(40.30)
ALICE	933.41^{D}	1034.00^{C}	1157.99^{B}	163.76^{D}	181.90^{C}	195.87^{B}
	(135.76)	(144.90)	(145.30)	(31.33)	(31.93)	(30.89)
LW II	1047.19^{C}	1165.13^{B}	1308.34^{A}	195.29^{C}	218.84^{B}	244.87^{A}
	(150.11)	(154.15)	(171.05)	(32.56)	(35.31)	(42.59)
MOLLE	810.26^{D}	955.63^{B}	1067.98^{A}	158.89^{C}	184.41^{B}	200.90^{A}
vs.	(75.80)	(80.51)	(83.75)	(18.25)	(22.78)	(20.92)
ALICE	792.17^{D}	927.25^{C}	1058.30^{A}	160.72^{C}	186.42^{B}	202.21^{A}
	(78.10)	(75.24)	(69.37)	(21.42)	(26.37)	(23.39)
MOLLE	1038.97^{E}	1201.24^{C}	1358.33^{A}	195.94^{D}	216.48^{C}	247.59^{A}
vs.	(138.62)	(139.25)	(134.75)	(39.14)	(34.12)	(42.69)
MLS	1027.73^{E}	1165.22^{D}	1296.24^{B}	197.79^{D}	211.91^{C}	231.73^{B}
	(109.73)	(149.41)	(149.19)	(36.10)	(44.79)	(37.55)

Note. For each dependent variable, means that do not share the same superscripts differed significantly ($p < .05$) on the Duncan post-hoc test from the other means between the same horizontal lines.

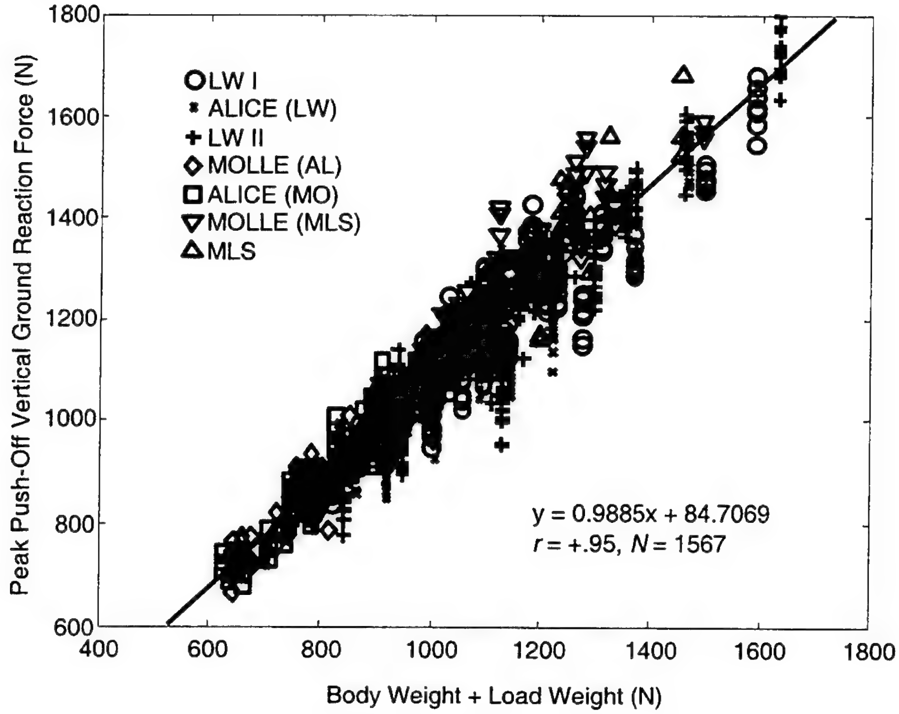

Figure 11. Scatter diagram and plot of simple linear regression equation for peak vertical ground reaction force at push-off as a function of body-plus-load weight.

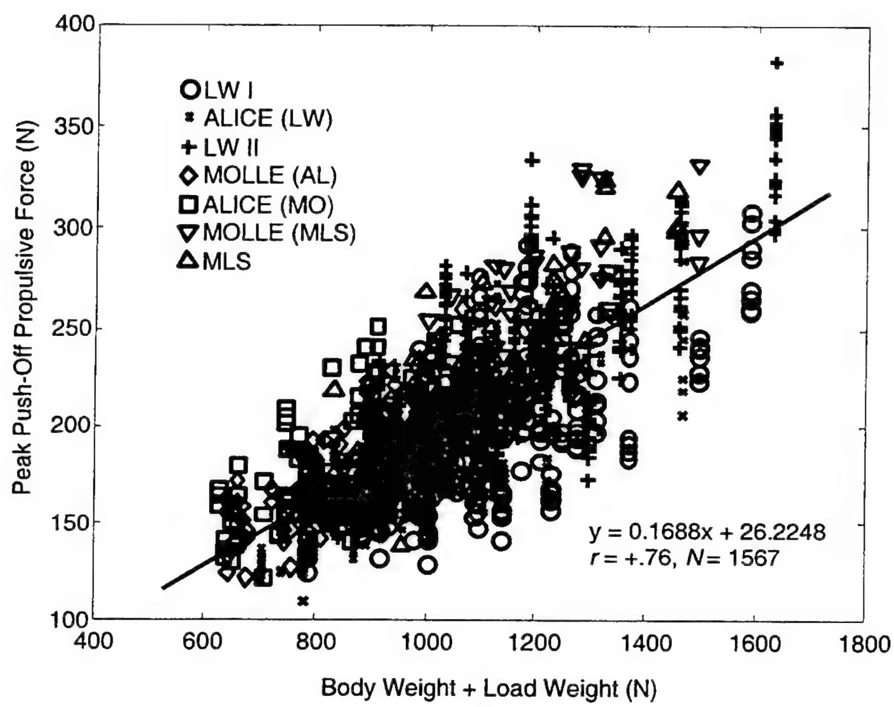

Figure 12. Scatter diagram and plot of simple linear regression equation for peak propulsive ground reaction force at push-off as a function of body-plus-load weight.

Stride-averaged GRFs. In Table 15, means from the original studies are presented for GRFs averaged over the entire stride. The specific GRFs included in the table are braking, propulsive, medial, and lateral forces. By convention, the braking and the medial forces are reported as negative numbers, with higher forces indicated by larger negative numbers. As can be seen in Table 15, the stride-averaged braking and propulsive GRFs increased significantly with weight carried. The stride-averaged medial force also showed a significant increase with weight carried, but, in some systems, only the lightest and the heaviest loads differed significantly. The stride-averaged lateral GRF did not show a consistent effect of weight carried, with a significant effect being obtained in only two of the four studies (Table 15).

Table 16 contains the results of the simple correlation and regression analyses performed on the stride-averaged GRFs. The correlations of the braking and the medial forces with body-plus-load weight were negative, due to the convention of reporting these forces as negative. It can be seen in Table 16 that the correlations of stride-averaged braking and propulsive GRFs with body-plus-load weight were substantial, Braking: $r(1565) = -.77, p < .01$; Propulsive: $r(1565) = +.68, p < .01$. About 60% of the variance in stride-averaged braking force and 46 % of the variance in stride-averaged propulsive force were attributable to body-plus-load weight. The regression equations for stride-averaged braking and propulsive GRFs are presented graphically in Figures 13 and 14, respectively. Compared to the relationships of braking and propulsive GRFs with body-plus-load weight, the correlations of stride-averaged medial and lateral GRFs with body-plus-load weight were relatively low, Medial: $r(1565) = -.36, p < .01$; Lateral: $r(1565) = +.20, p < .01$ (Table 16). Only about 13% of the variance in the medial force and 4% of the variance in the lateral force were attributable to body-plus-load weight.

Impulses over a stride. Means from the original studies for total impulse across a complete stride are presented in Table 17. The convention of expressing braking and medial impulses as negative numbers is followed, with higher impulses indicated by larger negative numbers. It can be seen in Table 17 that the braking and the propulsive impulses increased significantly with weight carried. The medial impulse over the entire stride also generally showed a significant increase with weight. However, the lateral impulse did not reveal a consistent effect of weight carried.

The results of the correlation and regression analyses of the impulses over the stride are presented in Table 18. The negative correlations of the braking and the medial impulses with body-plus-load weight are attributable to the convention of reporting these variables as negative numbers. Both the braking and the propulsive impulses were highly correlated with body-plus-load weight, Braking: $r(1565) = -.78, p < .01$; Propulsive: $r(1565) = +.72, p < .01$. The regression equations for the braking and the propulsive impulses are presented graphically in Figures 15 and 16, respectively. As can be seen in Table 18, the correlations of the medial and the lateral impulses with body-plus-load weight were relatively low.

Table 15
Means (and SDs) of Ground Reaction Forces Averaged Over a Stride (N)

	Braking GRF Load Configuration			Propulsive GRF Load Configuration			Medial GRF Load Configuration			Lateral GRF Load Configuration		
System	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.
LW I	-31.01^{B}	-35.23^{C}	-41.02^{E}	24.06^{D}	27.03^{B}	30.18^{A}	-15.58^{BC}	-16.99^{D}	-18.88^{E}	2.25^{A}	1.94^{BC}	1.84^{C}
vs.	(6.10)	(6.02)	(5.97)	(5.43)	(5.11)	(6.20)	(6.09)	(5.47)	(7.11)	(1.36)	(1.01)	(1.36)
MOLLE	-27.73^{A}	-30.59^{B}	-37.83^{D}	21.85^{E}	25.16^{C}	27.60^{B}	-13.03^{A}	-15.23^{B}	-16.58^{CD}	2.32^{A}	2.18^{AB}	1.92^{C}
	(5.01)	(5.80)	(7.91)	(4.99)	(4.87)	(5.29)	(4.70)	(4.83)	(5.89)	(0.98)	(0.89)	(1.37)
LW II	-29.08^{A}	-32.31^{B}	-38.10^{C}	27.44^{C}	32.43^{B}	36.32^{A}	-17.47^{A}	-18.45^{A}	-20.92^{B}	2.12^{A}	2.16^{A}	2.05^{A}
	(5.98)	(6.72)	(6.69)	(4.86)	(5.62)	(6.64)	(6.77)	(6.55)	(8.50)	(1.25)	(1.47)	(1.55)
MOLLE	-22.55^{A}	-27.42^{B}	-33.52^{C}	22.97^{C}	28.23^{B}	31.75^{A}	-12.53^{A}	-15.06^{B}	-17.07^{BC}	1.49^{A}	1.30^{A}	1.23^{A}
vs.	(3.56)	(3.94)	(5.94)	(2.74)	(3.86)	(3.59)	(4.43)	(4.36)	(4.63)	(0.76)	(0.60)	(0.91)
ALICE	-21.83^{A}	-25.83^{B}	-31.97^{C}	23.70^{C}	28.32^{B}	31.96^{A}	-12.46^{A}	-15.20^{B}	-17.32^{C}	1.52^{A}	1.31^{A}	1.32^{A}
	(3.58)	(3.81)	(5.35)	(3.62)	(3.81)	(3.34)	(5.39)	(5.62)	(7.18)	(0.88)	(0.68)	(0.80)
MOLLE	-32.61^{A}	-35.63^{B}	-41.51^{C}	27.11^{D}	31.35^{C}	36.37^{A}	-20.78^{ABC}	-22.04^{BC}	-23.07^{BC}	1.98^{ABC}	1.71^{C}	1.82^{BC}
vs.	(7.98)	(6.50)	(7.16)	(5.38)	(4.53)	(7.57)	(5.93)	(5.57)	(7.57)	(1.22)	(0.88)	(1.24)
MLS	-32.12^{A}	-36.34^{B}	-41.67^{C}	27.27^{D}	30.14^{C}	34.48^{B}	-18.73^{A}	-19.92^{AB}	-23.31^{C}	2.27^{A}	2.26^{A}	2.16^{AB}
	(6.02)	(5.91)	(7.59)	(4.84)	(5.82)	(5.22)	(5.83)	(6.16)	(9.63)	(1.13)	(1.69)	(1.63)

Note. For each dependent variable, means that do not share the same superscripts differed significantly ($p < .05$) on the Duncan post-hoc test from the other means between the same horizontal lines.

Table 16
Correlation Coefficients and Simple Linear Regression Equations for Ground Reaction Forces Averaged Over a Stride (y), in Newtons, as Functions of Body-Plus-Load Weight (x), in Newtons

Variable	r^a	Regression Equation		
Braking GRF	-.78*	y =	-0.0322x	+ 0.5156
Propulsive GRF	+.68*	y =	0.0245x	+ 3.4735
Medial GRF	-.36*	y =	-0.0133x	- 3.7303
Lateral GRF	+.20*	y =	0.0014x	+ 0.5525

$^a df = 1565$.
$^*p < .01$.

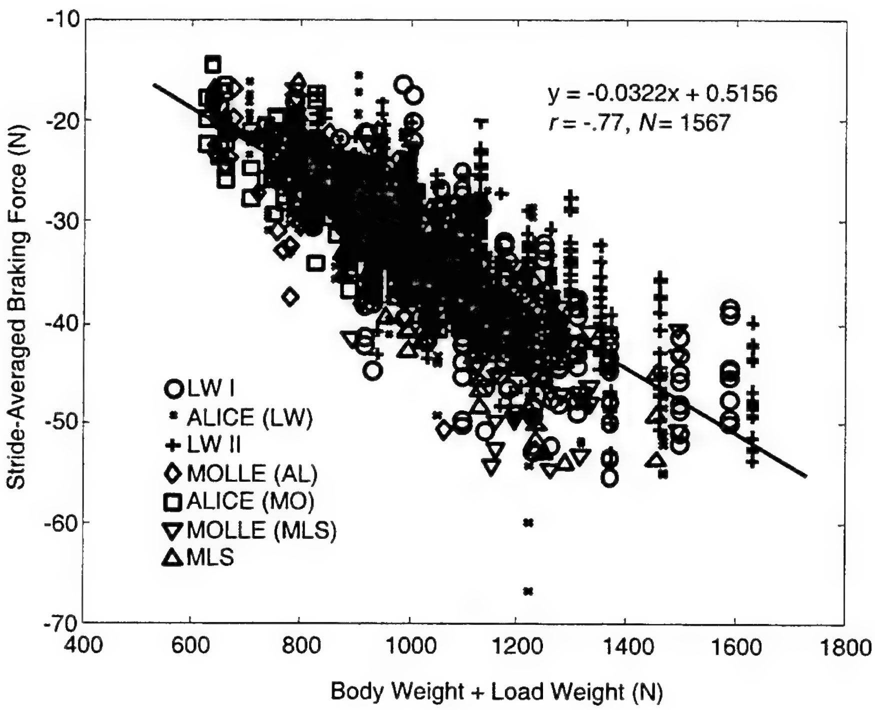

Figure 13. Scatter diagram and plot of simple linear regression equation for stride-averaged braking ground reaction force as a function of body-plus-load weight.

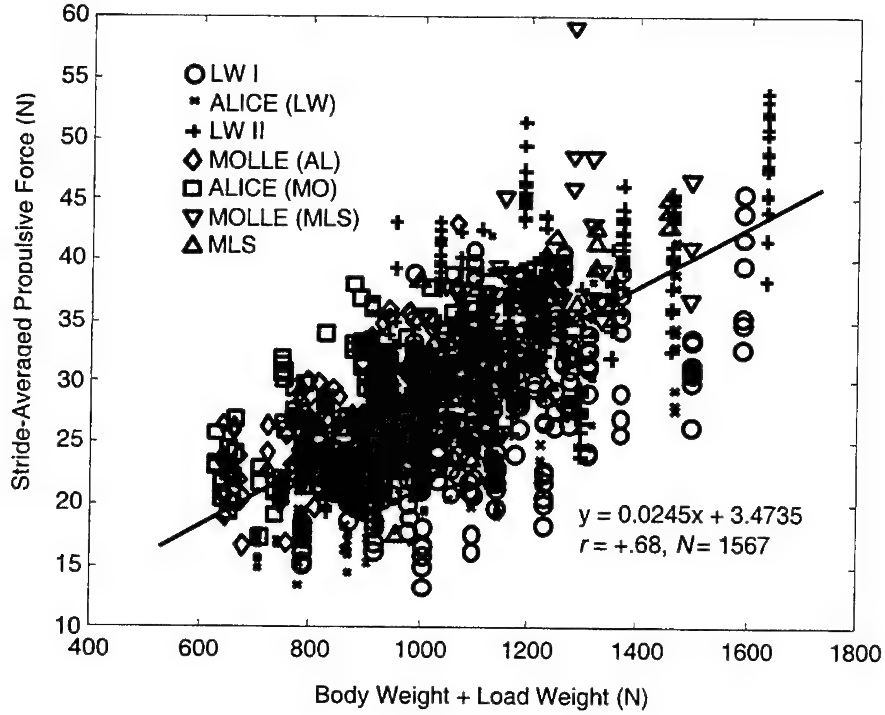

Figure 14. Scatter diagram and plot of simple linear regression equation for stride-averaged propulsive ground reaction force as a function of body-plus-load weight.

Table 17

Means (and SDs) of Various Impulses Measured Over a Full Stride (N·s)

	Braking Impulse Load Configuration			Propulsive Impulse Load Configuration			Medial Impulse Load Configuration			Lateral Impulse Load Configuration		
System	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.
LW I	-36.32^{B}	-41.74^{C}	-47.99^{E}	27.98^{D}	31.85^{B}	35.19^{A}	-18.17^{BC}	-20.00^{D}	-21.99^{E}	2.62^{A}	2.29^{BC}	2.15^{C}
vs.	(8.10)	(8.18)	(7.75)	(6.13)	(5.87)	(7.08)	(7.21)	(6.32)	(8.17)	(1.56)	(1.22)	(1.59)
MOLLE	-32.20^{A}	-35.76^{B}	-44.64^{D}	25.30^{E}	29.31^{C}	32.46^{B}	-15.07^{A}	-17.71^{B}	-19.45^{CD}	2.69^{A}	2.55^{AB}	1.27^{BC}
	(6.38)	(7.58)	(10.41)	(5.87)	(5.81)	(6.53)	(5.43)	(5.65)	(6.94)	(1.16)	(1.07)	(1.63)
LW II	-34.43^{A}	-33.32^{B}	-45.18^{C}	32.48^{C}	38.35^{B}	43.07^{A}	-20.58^{A}	-21.84^{A}	-24.71^{B}	2.51^{A}	2.56^{A}	2.43^{A}
	(7.40)	(8.59)	(8.14)	(6.09)	(6.96)	(8.15)	(7.87)	(7.87)	(9.91)	(1.50)	(1.74)	(1.85)
MOLLE	-24.35^{A}	-29.46^{C}	-35.56^{D}	24.83^{C}	30.34^{B}	33.63^{A}	-13.47^{A}	-16.10^{B}	-17.99^{BC}	1.62^{A}	1.40^{A}	1.32^{A}
vs.	(4.08)	(4.54)	(6.70)	(3.61)	(4.62)	(4.33)	(4.71)	(4.54)	(4.70)	(0.87)	(0.64)	(1.04)
ALICE	-23.25^{A}	-27.51^{B}	-34.11^{D}	23.18^{C}	30.14^{B}	34.15^{A}	-13.34^{A}	-16.21^{B}	-18.47^{C}	1.58^{A}	1.40^{A}	1.41^{A}
	(4.54)	(4.78)	(6.19)	(4.37)	(4.74)	(4.72)	(6.21)	(6.38)	(8.00)	(0.84)	(0.74)	(0.88)
MOLLE	-37.91^{A}	-42.38^{B}	-48.94^{C}	31.54^{D}	37.22^{C}	42.99^{A}	-24.22^{AB}	-26.14^{B}	-27.02^{B}	2.26^{ABC}	2.04^{C}	2.14^{BC}
vs.	(8.57)	(8.07)	(8.99)	(5.77)	(5.29)	(9.95)	(6.94)	(6.43)	(8.57)	(1.28)	(1.02)	(1.46)
MLS	-38.14^{A}	-43.07^{B}	-49.14^{C}	32.32^{D}	35.66^{C}	40.57^{B}	-22.19^{A}	-23.66^{AB}	-27.39^{B}	2.68^{A}	2.64^{A}	2.54^{AB}
	(7.58)	(6.84)	(9.73)	(5.87)	(6.43)	(6.41)	(6.99)	(7.56)	(11.35)	(1.32)	(1.90)	(1.95)

Note. For each dependent variable, means that do not share the same superscripts differed significantly ($p < .05$) on the Duncan post-hoc test from the other means between the same horizontal lines.

Table 18
Correlation Coefficients and Simple Linear Regression Equations for Impulses Measured Over a Full Stride (y), in Newton-seconds, as Functions of Body-Plus-Load Weight (x), in Newtons

Variable	r^{a}	Regression Equation		
Braking Impulse	-.78*	y =	-0.0413x	+ 4.4002
Propulsive Impulse	+.72*	y =	0.0321x	+ 0.3666
Medial Impulse	-.40*	y =	-0.0174x	- 2.2889
Lateral Impulse	+.23*	y =	0.0018x	+ 0.4324

[a] *df* = 1565.
**p* < .01.

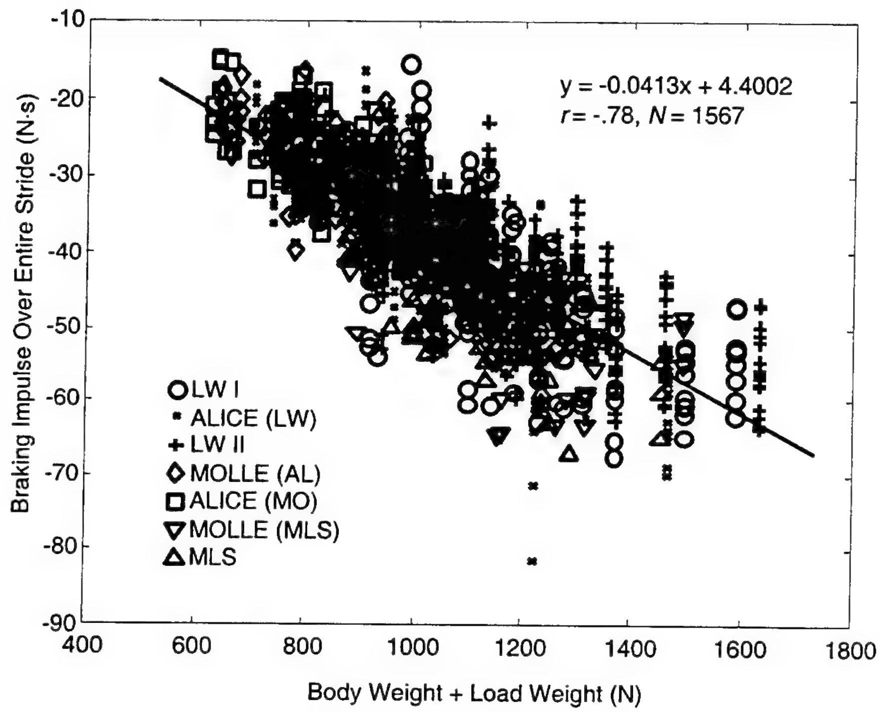

Figure 15. Scatter diagram and plot of simple linear regression equation for braking impulse over a full stride as a function of body-plus-load weight.

Joint Reaction Force Variables

Both maximum joint reaction forces and joint reaction forces averaged over a stride were calculated for the ankle, the knee, and the hip. As was done for the GRFs, body-plus-load weight was used as the independent variable in the correlation and regression analyses.

Maximum joint reaction forces. The means from the four, original studies for the maximum reaction forces at the joints are presented in Table 19. As indicated in the table, the reaction forces at each joint increased significantly with load.

The results of the linear correlation and regression analyses performed on the maximum reaction forces at the ankle, the knee, and the hip are presented in Figures 17, 18, and 19, respectively. It can be seen in the figures that very high, positive correlations were obtained between the maximum reaction forces at these joints and body-plus-load weight. Approximately 90% of the variance in the joint forces was attributable to body-plus-load weight (Ankle: $r^2 = .92$; Knee: $r^2 = .90$; Hip: $r^2 = .90$). The slopes of the regression equations approach a 1-N increase in maximum reaction force for each 1-N increase in body-plus-load weight. Furthermore, the values for the slopes decrease from ankle to hip (Figures 17-19). Thus, the reaction forces at the more proximal joints increased less sharply with increases in body-plus-load weight than did those at the more distal joints. The results of an ANOVA indicate that the slopes of the regression equations differed significantly, $F(2, 4695) = 30.78, p < .001$).

Joint reaction forces over a stride. Table 20 is a listing of the means from the original studies for the joint reaction forces averaged over a stride. As was the case with the maximum reaction forces, the stride-averaged reaction forces at each joint increased significantly with load in each of the original studies.

The results of the linear correlation and regression analyses performed on the stride-averaged reaction forces at the ankle, the knee, and the hip are presented in Figures 20, 21, and 22, respectively. Again, very high, positive correlations were obtained between the joint reaction forces and body-plus-load weight. Approximately 96% of the variance in the joint forces was attributable to body-plus-load weight (Ankle: $r^2 = .96$; Knee: $r^2 = .96$; Hip: $r^2 = .96$). As can be seen in the figures, the slopes of the regression equations for the stride-averaged forces are not as steep as the slopes for the maximum forces. As expected, because each leg supports only half the body weight on average, the slopes were in the vicinity of 0.5. Specifically, there was an increase in stride-averaged forces of from 0.44 N to 0.47 N for each 1-N increase in body-plus-load weight. As was the case for the maximum joint reaction forces, the slopes of the stride-averaged forces were higher for the more distal than for the more proximal joints, again indicating that the reaction forces at the more distal joints increased more sharply with increases in body-plus-load weight than did those at the more proximal joints (Figures 20-22). The slopes of the regression equations for the stride-averaged reaction forces at the three joints were found via ANOVA to differ significantly, $F(2, 4695) = 36.76, p < .001$).

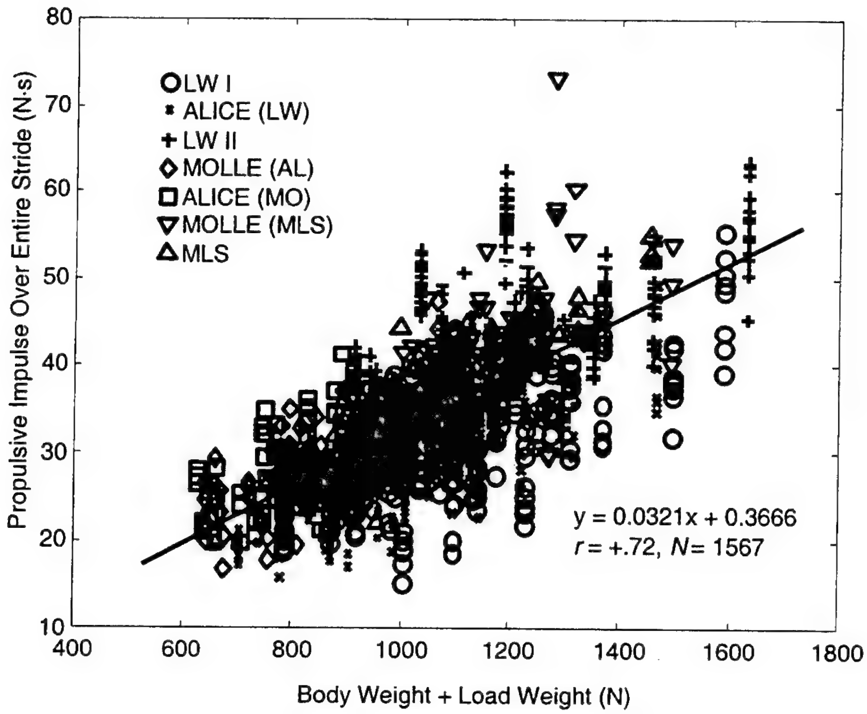

Figure 16. Scatter diagram and plot of simple linear regression equation for propulsive impulse over a full stride as a function of body-plus-load weight.

Table 19
Means (and SDs) of Maximum Joint Reaction Forces (N)

	Ankle Reaction Force			Knee Reaction Force			Hip Reaction Force		
	Load Configuration			Load Configuration			Load Configuration		
System	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.
LW I	1056.27^{D}	1181.35^{C}	1345.75^{A}	1025.48^{D}	1145.39^{C}	1308.32^{A}	961.76^{D}	1074.67^{C}	1233.68^{A}
vs.	(137.42)	(124.93)	(121.99)	(133.80)	(118.95)	(116.01)	(129.42)	(110.98)	(107.83)
ALICE	966.80^{E}	1062.01^{D}	1217.23^{B}	934.18^{E}	1028.24^{D}	1184.07^{B}	871.77^{E}	961.91^{D}	1116.93^{B}
	(121.89)	(135.56)	(132.39)	(116.96)	(130.52)	(129.44)	(109.07)	(121.88)	(123.49)
LW II	1062.37^{C}	1187.96^{B}	1353.02^{A}	1025.30^{C}	1150.11^{B}	1315.83^{A}	950.73^{C}	1073.74^{B}	1240.53^{A}
	(148.13)	(141.19)	(139.82)	(142.63)	(135.50)	(133.71)	(130.35)	(124.85)	(123.32)
MOLLE	831.00^{D}	985.76^{B}	1101.80^{A}	802.41^{D}	957.94^{B}	1075.36^{A}	750.35^{C}	902.34^{B}	1021.68^{A}
vs.	(78.91)	(69.58)	(88.22)	(77.75)	(65.74)	(84.31)	(72.01)	(60.56)	(75.10)
ALICE	819.77^{D}	962.30^{C}	1099.51^{A}	793.04^{D}	936.53^{C}	1072.60^{A}	743.83^{C}	882.37^{B}	1018.09^{A}
	(78.42)	(71.18)	(59.58)	(78.08)	(70.49)	(60.60)	(81.63)	(69.61)	(60.49)
MOLLE	1100.67^{E}	1229.84^{C}	1389.79^{A}	1060.91^{E}	1193.01^{C}	1351.45^{A}	986.89^{E}	1117.86^{C}	1274.94^{A}
vs.	(148.87)	(134.56)	(145.80)	(143.47)	(133.59)	(144.25)	(139.22)	(131.31)	(140.86)
MLS	1091.10^{E}	1195.82^{D}	1335.50^{B}	1053.21^{E}	1156.54^{D}	1296.62^{B}	983.31^{E}	1077.69^{D}	1215.11^{B}
	(139.85)	(147.58)	(160.33)	(137.68)	(142.85)	(156.02)	(140.62)	(138.28)	(148.64)

Note. For each dependent variable, means that do not share the same superscripts differed significantly ($p < .05$) on the Duncan post-hoc test from the other means between the same horizontal lines.

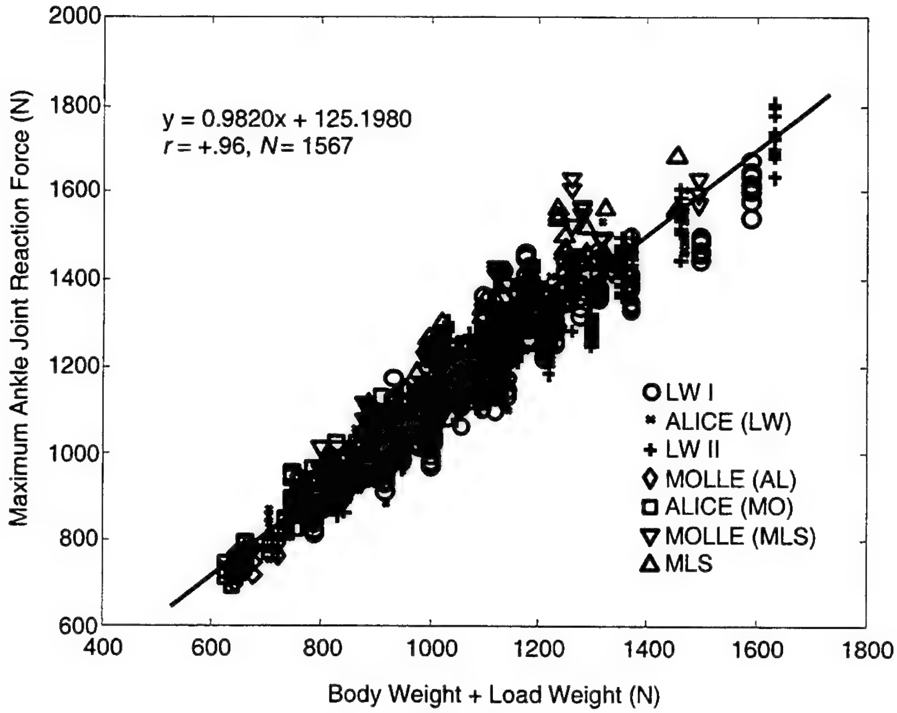

Figure 17. Scatter diagram and plot of simple linear regression equation for maximum ankle joint reaction force as a function of body-plus-load weight.

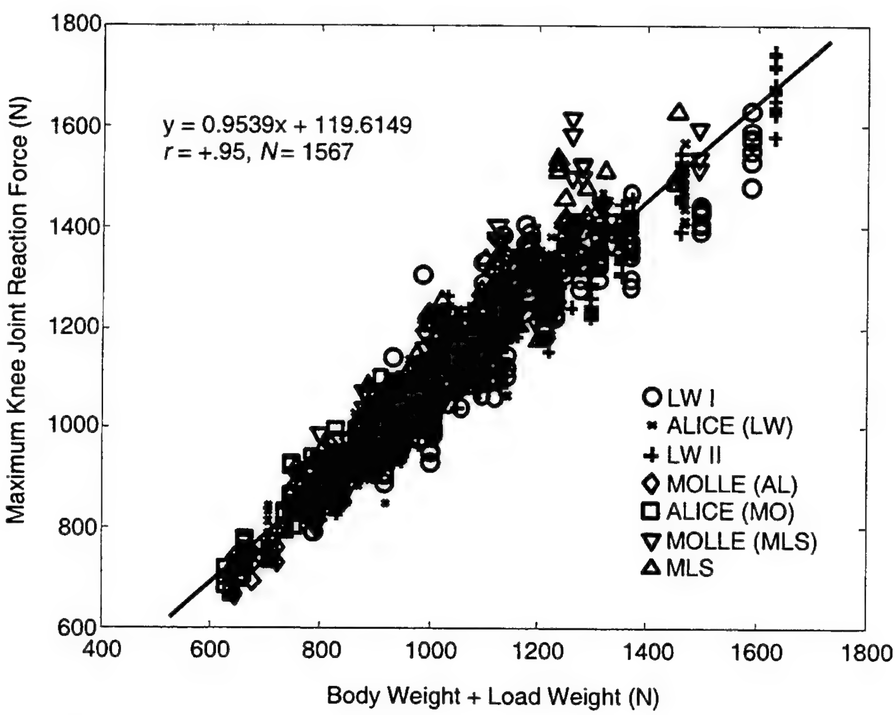

Figure 18. Scatter diagram and plot of simple linear regression equation for maximum knee joint reaction force as a function of body-plus-load weight.

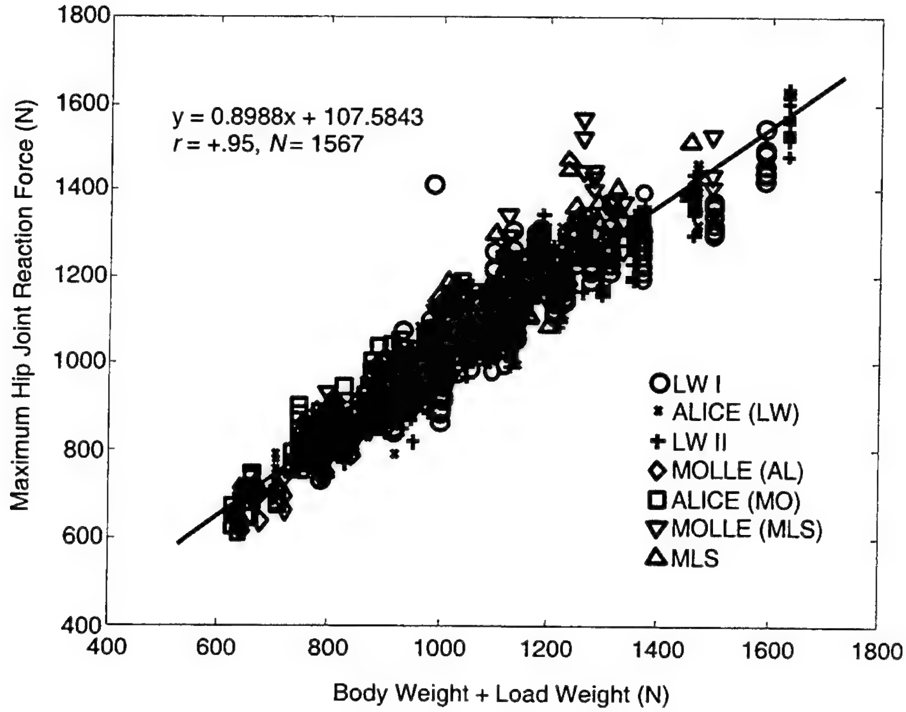

Figure 19. Scatter diagram and plot of simple linear regression equation for maximum hip joint reaction force as a function of body-plus-load weight.

Table 20
Means (and SDs) of Joint Reaction Forces Averaged Over a Stride (N)

	Ankle Reaction Force Load Configuration			Knee Reaction Force Load Configuration			Hip Reaction Force Load Configuration		
System	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.	Fighting	Approach	Sustain.
LW I	474.24^{D}	528.83^{C}	598.09^{A}	463.71^{D}	517.76^{C}	587.29^{A}	445.62^{D}	497.91^{C}	566.80^{A}
vs.	(66.52)	(66.67)	(62.49)	(64.39)	(64.45)	(60.61)	(61.46)	(60.64)	(57.39)
ALICE	430.00^{E}	473.69^{D}	541.20^{B}	419.60^{E}	463.09^{D}	530.58^{B}	402.64^{E}	445.14^{D}	511.41^{B}
	(64.53)	(66.42)	(68.21)	(62.37)	(64.59)	(67.48)	(59.09)	(60.94)	(64.38)
LW II	471.93^{C}	528.70^{B}	602.47^{A}	460.95^{C}	517.96^{B}	591.29^{A}	442.13^{C}	497.83^{B}	570.00^{A}
	(68.26)	(66.76	(68.05)	(66.38)	(64.83)	(66.09)	(63.33)	(61.48)	(62.64)
MOLLE	362.94^{D}	437.93^{B}	500.53^{A}	355.78^{D}	431.65^{B}	494.13^{A}	341.74^{D}	414.63^{B}	476.73^{A}
vs.	(35.27)	(45.48)	(50.18)	(35.04)	(47.56)	(52.10)	(33.05)	(43.70)	(47.92)
ALICE	360.15^{D}	416.25^{C}	493.95^{A}	354.91^{D}	409.18^{C}	488.07^{A}	340.96^{D}	394.08^{C}	470.22^{A}
	(44.66)	(36.35)	(48.84)	(47.47)	(36.28)	(53.36)	(44.43)	(33.50)	(49.72)
MOLLE	467.65^{E}	527.88^{C}	596.52^{A}	457.17^{E}	517.49^{C}	585.84^{A}	439.06^{E}	498.53^{C}	565.37^{A}
vs.	(77.03)	(66.74)	(60.36)	(76.42)	(65.44)	(58.82)	(72.12)	(62.65)	(56.68)
MLS	462.28^{E}	514.95^{D}	584.60^{B}	451.54^{E}	504.30^{D}	573.37^{B}	434.52^{E}	485.21^{D}	551.48^{B}
	(63.52)	(64.77)	(65.36)	(61.71)	(63.30)	(64.04)	(59.66)	(61.11)	(61.30)

Note. For each dependent variable, means that do not share the same superscripts differed significantly ($p < .05$) on the Duncan post-hoc test from the other means between the same horizontal lines.

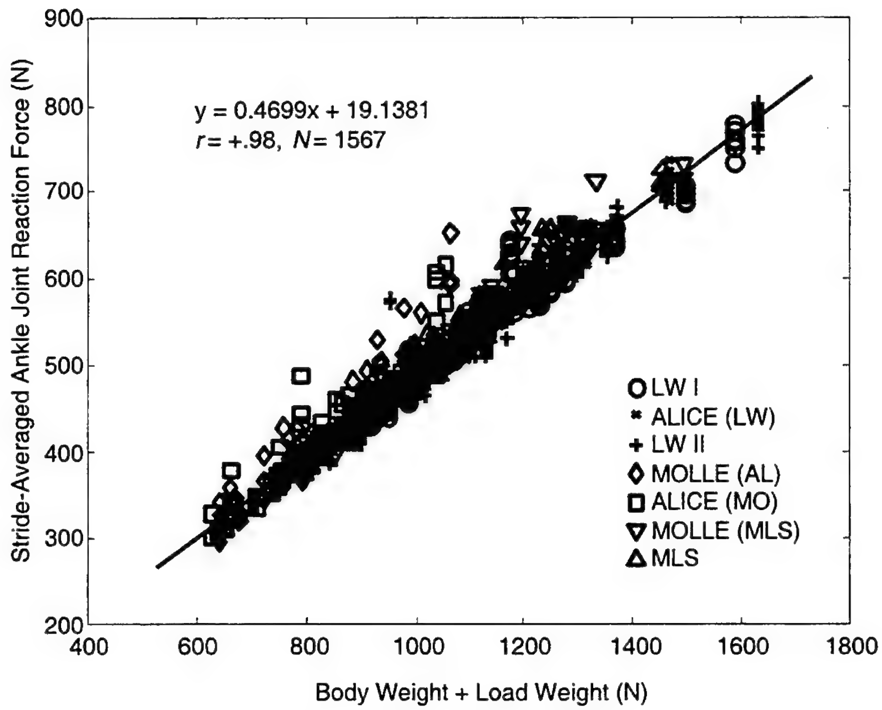

Figure 20. Scatter diagram and plot of simple linear regression equation for ankle joint reaction force averaged over a stride as a function of body-plus-load weight.

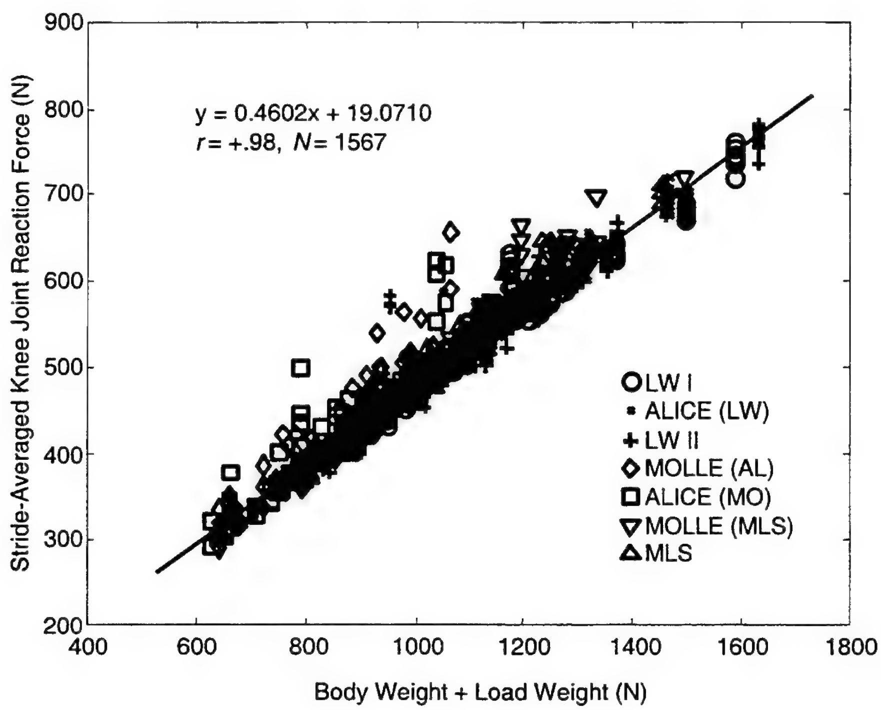

Figure 21. Scatter diagram and plot of simple linear regression equation for knee joint reaction force averaged over a stride as a function of body-plus-load weight.

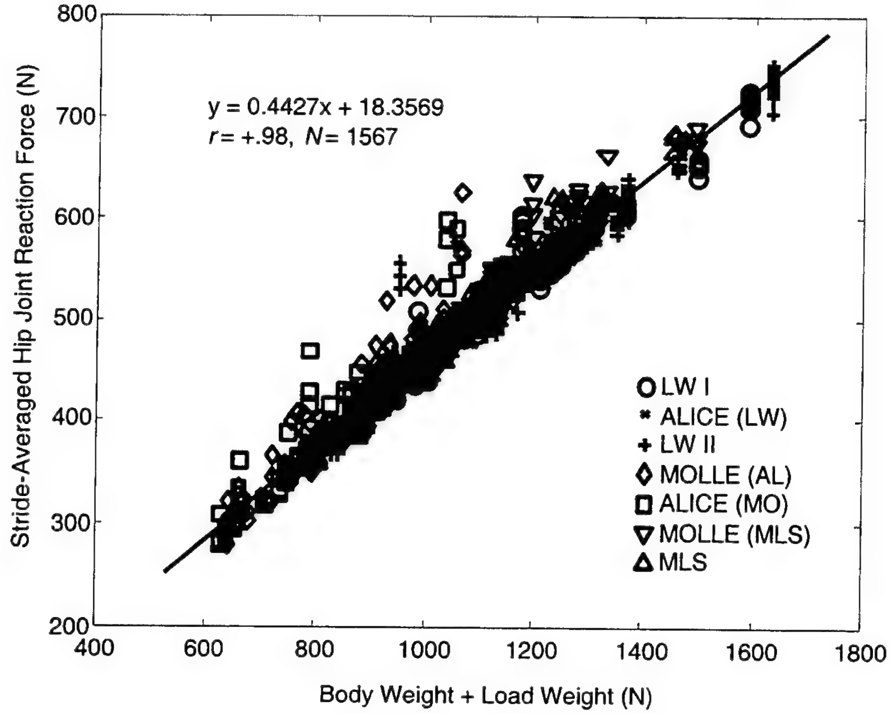

Figure 22. Scatter diagram and plot of simple linear regression equation for hip joint reaction force averaged over a stride as a function of body-plus-load weight.

Discussion

Missions performed by U.S. military ground troops often entail marching with loads to a destination and then immediately undertaking a tactical operation, such as engaging the enemy (Department of the Army, 1990). The success of a mission is often highly dependent upon the march being completed quickly. Furthermore, the most critical part of a mission, as well as the most physically and psychologically challenging one, may occur after soldiers have completed the march (Marshall, 1950/1980). Data from the four studies examined here illustrate the physical demands and negative impacts on performance that the weights of loads carried during foot marches impose on soldiers and, thus, the risk to mission success that military loads represent. The data also reveal the substantial burden that heavy loads place on the individual soldier's musculoskeletal system and, thus, the risk of injury that is associated with carrying loads.

The maximal performance test included in the studies required that participants travel 3.2 km, a relatively short distance for a foot march. Linear regression analysis of the pooled data from two of the three studies in which men served as the participants revealed that, over the range of load weights tested, there was an increase of approximately 1.7 s in time to cover the 3.2-km distance for each 1-N increase in the weight carried. From the regression equation for the men, it can be estimated that a male soldier who completed the course in 20 min carrying a mass of 16 kg would require over 28 min to complete the course when carrying a 48-kg load. The data from the one study in which women served as the participants revealed an even greater negative impact of load weight on time to traverse a distance of 3.2 km. For the women, there was an increase of approximately 2.4 s in the travel time for each 1-N increase in weight over the range of load weights tested.

The women's higher rate of increase in course completion time as a function of weight carried may be attributable, in part, to the fact that the women were generally smaller than the men. Thus, a given load represented a greater proportion of a woman's body mass. In their study of load carrying by men and women, Martin and Nelson (1985) also found that men consistently outperformed women on maximal performance tests. The tests used by Martin and Nelson included running and jumping, and load masses ranged from approximately 1 kg to 36 kg. Martin and Nelson maintained that a major contributor to the inferior performance of the women was the higher percentage of their body mass that is adipose tissue, as opposed to muscle. For the women in their study, an average of 23.4% of body mass was fat; for the men, the average was 16.8%. Although measurements for estimating body fat were not made on the participants in the four studies analyzed in this report, it is likely that the female participants had higher percentages of body fat than the males did. Thus, as was the case in the study conducted by Martin and Nelson, a given load probably represented a greater proportion of a woman's lean body mass than a man's.

The weight soldiers carry not only affects the speed of overground movements, as evidenced by the time to complete the 3.2-km march, it affects the amount of energy that

soldiers expend during a foot march. The metabolic cost of carrying loads is a great concern to the military because, the higher the energy cost of the march, the less likely it is that soldiers will have the physical stamina to deal successfully with the post-march challenges of a mission (Department of Defense, 1990). In this summary report, one measure of energy cost analyzed was oxygen uptake expressed as a percentage of maximal oxygen uptake. Regression analyses revealed an increase of approximately 0.03% of $\dot{V}O_{2max}$ for the men and 0.05% of $\dot{V}O_{2max}$ for the women for each 1-N increase in weight carried over the range of loads tested. Thus, as was the case for time to complete the 3.2-km course, the women paid a greater penalty than the men when carrying increasingly heavy loads.

For the energy cost testing, the participants in the studies analyzed here walked at a pace of 4.8 $km \cdot hr^{-1}$ for the relatively short time of 5 min, covering a distance of 0.4 km. Patton et al. (1991) had their subjects, 15 men, walk at this approximate pace for a distance of 12 km. They found that, depending upon the mass of the load being carried and the pace of the march, energy cost increased over time by 10% to 18%. Based upon the results reported by Patton et al., it is possible that the metabolic costs as a function of weight carried would have been even greater in the studies reported here if the duration of the march period had been longer.

Examination of the kinetics of walking along a horizontal path at 4.8 $km \cdot hr^{-1}$ revealed that heavy loads place a substantial burden on the soldier's musculoskeletal system. Peak vertical ground reaction forces at heel-strike and at push-off were positively and highly correlated with body-plus-load weight. Approximately 88% of the variance in peak vertical force at heel-strike and 90% of the variance in peak vertical force at push-off were attributable to body-plus-load weight. The linear regression equations indicated that peak vertical forces at heel-strike and at push-off increased by almost 1 N for each 1-N increase in body-plus-load weight. Thus, the vertical forces experienced as the foot strikes the ground at the beginning of a gait cycle and as the foot leaves the ground later in the cycle are primarily due to the direct effect of body-plus-load weight. The repeated exposure of the body to the high-magnitude, vertical forces as the foot contacts and subsequently pushes off from the ground during locomotion has been implicated in the occurrence of acute and chronic injuries, particularly overuse injuries of the lower extremities (James, Bates, & Osternig, 1978; Knapik et al., 1996).

Peak braking force at heel-strike and peak propulsive force at push-off were also highly correlated with body-plus-load weight, but the correlations did not reach the values that those associated with vertical ground reaction forces did. About 50% of the variance in peak braking force and 58% of the variance in peak propulsive force were attributable to body-plus-load weight. The rates of increase in the braking and the propulsive forces with increases in body-plus-load weight were also not as great as the increases in the vertical forces. Based upon the linear regression equations, it can be estimated that peak braking force at heel-strike and peak propulsive force at push-off increase by approximately 0.17 N with each 1-N increase in body-plus-load weight.

In addition to examining peak braking and propulsive ground reaction forces during the stride, averages of these two forces and their related impulses over a stride

were examined. As expected, the average values were considerably lower than their respective peaks. The regression equations indicated an increase in these forces of about 0.03 N for each 1-N increase in body-plus-load weight over the range of weights tested. However, the braking and the propulsive forces averaged over a stride were still highly correlated with body-plus-load weight. Approximately 61% of the variance in stride-averaged braking force and 46% of the variance in stride-averaged propulsive force were attributable to body-plus-load weight. The results for the braking and the propulsive impulses over a full stride were affected by increases in load very similarly to the results for the braking and propulsive forces.

The medial and the lateral ground reaction forces were examined by calculating both the average of each of these forces over a stride and the impulse over a full stride. The magnitudes of the medial and the lateral ground reaction force variables were lower than the comparable braking and propulsive force variables, with the lateral ground reaction forces being the lowest in magnitude. In addition, the correlations of the stride-averaged medial and lateral forces and impulses with body-plus-load weight were quite low. Kinoshita (1985), in his study of the biomechanical effects of loads that were 0%, 20%, and 40% of body mass, also found little change in the medial and the lateral forces with changes in weight carried.

Ground reaction forces mirror the forces exerted by the ground on the foot during the gait cycle, but do not reveal the magnitude of the forces within the skeleton during ground contact. For the studies analyzed here, internal forces at the lower extremity joints were calculated using the inverse dynamics method. The repeated impulse loading at the various joints of the body has been associated with degenerative changes in the weight-bearing joints of animals (Aroski, Kirviranta, Jurvelin, Tammi, & Helminen, 1993; Lukoshcek, Boyd, Schaffler, Burr, & Radin, 1986; Radin et al., 1984; Serink, Nachemson, & Hansson, 1997) and with progressive degeneration of articular joint surfaces in humans (Buckwalter, 1995). The loading at a joint is the amount of load borne by the joint in terms of body-plus-load weight, the dynamic acceleration of the load, and dynamic muscle action at the joint. The mathematical model used in these studies to estimate the internal forces on the ankle, the knee, and the hip joints did not account for possible muscle co-contraction. Therefore, the reaction forces presented here likely underestimate the forces experienced at the joints. Quantification of joint reaction force is still useful, however, for estimating increases in forces within the joints as the load on a soldier is increased.

The maximum joint reaction forces and the average joint reaction forces over a stride were calculated for the ankle, the knee, and the hip. Both joint reaction force variables were highly and positively correlated with body-plus-load weight. About 90% of the variances in the maximum forces and 96% of the variances in the stride-averaged forces were attributable to body-plus-load weight. The slopes of the linear regression equations for both joint reaction force variables decreased from ankle to hip. Thus, the reaction forces at the more proximal joints increased at a less rapid rate with increases in body-plus-load weight than did those at the more distal joints, indicating some attenuation as the forces were transmitted from the ground up through the leg.

Although there were differences in the slopes associated with the regression equations for the different joints, the slopes calculated for the stride-averaged forces indicated that forces at all three joints analyzed increased considerably, by 0.44 N to 0.47 N with each 1-N increase in body-plus-load weight over the range of weights tested. The slopes of the linear regression equations for the maximum reaction forces at the three joints were even steeper, approaching a 1-N increase in joint reaction force for each 1-N increase in body-plus-load weight. It would appear, therefore, that, over the range of load weights tested in the four studies analyzed here, the risk of injury to the joint increases steadily as the load the soldier carries increases.

There are changes in gait kinematics associated with the carrying of loads that may serve to reduce the magnitude of the forces that are imposed on the body as a result of contact of the foot with the ground. The kinematic changes may also aid in the maintenance of postural stability (Harman et al., 2000; Kinoshita, 1985; Martin & Nelson, 1986; Quesada et al., 2000). Martin and Nelson found an increased forward inclination of the trunk when a backpack with a mass of approximately 13 kg was carried compared with a condition in which no backpack was used. Kinoshita also reported increased trunk lean when a backpack load equaling 40% of body mass was being carried compared with a pack load equaling 20% of body mass. He proposed that the inclined posture facilitated forward propulsion of the body into the next step. Harman et al. maintained that the forward trunk lean under a backpack load is necessary for keeping the center of mass of the body-plus-load system over the base of support (i.e., the feet) to prevent falling. They also stated that the forward lean keeps the center of mass lower, which likely increases stability when walking over rough terrain.

In consonance with the findings of Kinoshita (1985) and of Martin and Nelson (1986), the minimum and the maximum trunk angle data analyzed here revealed that the forward inclination of the trunk increased with increases in weight carried. Both trunk angle variables were highly and positively correlated with weight; approximately 65% of the variance in these measures was attributable to the weight carried. Minimum and maximum trunk lean increased by about 0.04 degrees with each 1-N increase in load weight over the range of weights tested. The range of movement of the trunk over a stride had a small, but definite, positive relationship with weight carried; about 10% of the variance in trunk range of movement was accounted for by weight carried.

Hip angle is influenced by both the trunk and the knee angles. Harman et al. (2000), in an investigation of the kinematic and kinetic effects of backpack loads ranging from 6 kg to 47 kg in 14-kg increments, found that both the minimum and the maximum hip angles over a stride decreased as the weight being carried increased. Their post-hoc tests on the means for the load conditions revealed statistically significant decreases in minimum and in maximum hip angles with each 14-kg increment in pack weight. Harman et al. maintained that the greater extent of hip flexion was largely accounted for by the increased forward inclination of the trunk that occurred as the weight carried increased.

The analyses performed on the individual data of the four studies examined here also showed that hip flexion increased with load weight. The linear regression analyses

of the pooled data from the four studies yielded moderate, negative correlations of minimum and of maximum hip angle with weight carried; greater weight carried was associated with smaller angles, and thus greater flexion at the hip. About 46% of the variance in minimum hip angle and 27% of the variance in maximum hip angle were attributable to the weight carried. The regression equations for the minimum and the maximum hip angles indicated that the slopes of the regression of hip angle on weight carried approximated the regression slopes for the minimum and maximum trunk angles. That is, hip flexion increased by about 0.04 degrees for each 1-N increase in load weight over the range of weights tested. This finding supports the proposal by Harman et al. (2000) that increases in hip flexion with increases in the load carried are due to the greater trunk inclination that also accompanies load increases.

Kinoshita (1985) found that knee flexion was greater with a heavier than with a lighter load. He proposed that the knee joint, together with the thigh muscles, function as a shock absorber to reduce the magnitude of the forces to which the body is exposed during ground contact. Harman et al. (2000), in their investigation of loads ranging from 6 kg to 47 kg in 14-kg increments, also found that minimum and maximum flexion at the knee tended to increase with load weight. However, their post-hoc tests contrasting the means for the load conditions yielded statistically significant differences only between the extreme loads. For minimum knee flexion, the significant differences were limited to the contrast of the 6-kg and the 47-kg loads. For maximum knee flexion, the 33-kg and the 47-kg loads differed significantly from the 6-kg load; there were no other significant differences among the load conditions. Harman et al. suggested that, in addition to aiding in shock absorption, the greater knee flexion serves to keep the center of mass of the body-plus-load system low, contributing to the stability of the system.

For the minimum and the maximum knee angles in the studies reported here, the analyses performed on the data of the individual studies yielded statistically significant differences among some of the load conditions tested in a given study. There was an indication that minimum knee angle tended to increase and maximum knee angle tended to decrease as the weight carried increased. However, as was found by Harman et al. (2000), there was not a clear relationship between these knee angle variables and load weight. Furthermore, the correlations of minimum and maximum knee angles with load weight, which were calculated on the pooled data from all four studies, were slight, indicating a negligible linear relationship between these knee angle variables and the weight of the load carried. On the other hand, the correlation of range of knee angle with load weight was small, but indicated a definite negative relationship between range of movement at the knee and load weight. The range of knee movement decreased by about 0.01 degrees with each 1-N increase in load over the range of weights tested. The fact that the range of knee angle data did show a definite, negative relationship with load weight suggests that the load being carried does have a linear effect on movement at the knee, although the effect may be a small one.

Kinoshita (1985) also reported greater dorsiflexion at the ankle when a backpack load equaling 40% of body mass was being carried compared with a pack load equaling 20% of body mass. The results obtained by Harman et al. (2000) in their investigation of

pack loads ranging from 6 kg to 47 kg did not support this finding. Harman et al. did not find changes in the minimum, the maximum, or the range of ankle angle over a stride with the load weights tested. Similarly, the correlations calculated from the pooled data of the four studies examined here revealed that load weight has a negligible relationship with the minimum and the maximum ankle angle variables. However, with regard to range of ankle angle, the correlation of this variable with load weight was small, but significant. The range of motion at the ankle increased by about 0.01 degrees for each 1-N increase in the load carried over the range of loads tested. Therefore, as was found for range of movement at the knee, load weight does have at least a small effect on range of movement at the ankle.

In investigating effects of backpack loads on gait kinematics, Harman et al. (2000) suggested that increased trunk inclination and increased hip flexion reduce the height of the center of mass and that this lowering of the center of mass contributes to the stability of the body-plus-load system. In analyses of the vertical position of the body center of mass, they found that the minimum and the maximum vertical positions decreased as the weight carried increased. Their post-hoc tests performed on the means for the load conditions indicated that minimum vertical center of mass height values for the two highest load weights, 33 kg and 47 kg, did not differ from each other, but were significantly lower than the values for the 6-kg and the 20-kg loads, which also did not differ from each other. With regard to maximum center of mass height, again the means for 33-kg and the 47-kg loads did not differ from each other, but they were significantly lower than the means for 6-kg and the 20-kg loads. In addition, the 20-kg load had a mean that was significantly lower than that for the 6-kg load.

The results obtained in the four studies summarized here were similar to those of Harman et al. (2000). The analyses performed on the individual studies revealed trends toward decreasing minimum and maximum center of mass heights as the weight carried increased, with the most distinct differences in the values occurring between the highest and the lowest weights. The correlations calculated on the pooled data of all four studies revealed small, but definite, negative relationships between the two center of mass height variables and weight carried. About 6% of the variances in minimum and in maximum vertical center of mass heights were attributable to the weight of the load carried.

In the four studies analyzed in this report, participants walked at a pace of 4.8 $km \cdot hr^{-1}$ while the biomechanics measurements were recorded. Two variables were analyzed to investigate temporal gait patterns. These were double-support duration and stride frequency. Kinoshita (1985) also controlled the walking speed of his study participants; speed was set at 4.5 $km \cdot hr^{-1}$. He found that the proportion of the gait cycle spent in double support increased with the load carried. Harman et al. (2000) analyzed the double-support variable in their study in which men walked at 4.0, 4.7, and 5.4 $km \cdot hr^{-1}$ while carrying loads of 6 to 47 kg. They also reported that the percentage of the stride cycle spent in double support generally increased as the weight carried increased. The post-hoc tests that Harman et al. conducted on the means for the load weight conditions indicated that only the means for extremely different loads differed significantly. The percentage of double-support time with the 47-kg load was

significantly greater than the percentages for the 6-kg and the 20-kg loads; there were no other statistically significant differences among the load conditions. Harman et al. proposed that the increase in double-support time results in improved stability. The double-support period is the portion of the gait cycle when the body has the largest base of support, and is thus most stable. It is possible, as well, that increasing the time spent with both feet in contact with the ground decreases the internal load on the joints in each lower extremity.

The analyses of the data from the individual studies examined in this report indicated a trend toward an increased percentage of the stride cycle being spent in double support with increased load. The correlation calculated on the pooled data from the four studies revealed that there was a small, but significant, positive relationship between the percentage of stride spent under double support and weight carried. Weight carried accounted for approximately 14% of the variance in double-support duration. Based upon the linear regression equation, the increase in the percentage of the stride cycle spent in double support is estimated to be less than 0.01% of the cycle for each 1-N increase in weight carried over the range of weights tested. Therefore, the data presented here support the findings of Harman et al. (2000) that, although there is an increase in double-support duration with increases in weight carried, double-support duration does not have a particularly strong linear relationship with the weight carried.

Martin and Nelson (1986) tested men and women walking at 6.4 $km \cdot hr^{-1}$. They found that stride frequency increased with load weight. Walking velocity is the product of stride frequency and stride length. Martin and Nelson held walking velocity constant. Thus, the increasing stride frequency was accompanied by decreasing stride length as load weight increased. Like Martin and Nelson, Harman et al. (2000) found that stride frequency increased with weight carried. Post-hoc analyses of the means for their load conditions revealed that stride frequency with a 47-kg load was significantly higher than it was with loads of 6, 20, or 33 kg. There were no other differences among the load weight conditions. Thus, the findings of Harman et al. for stride frequency are similar to their findings for double-support duration: Load weight affected both temporal variables, but neither variable evidenced a particularly strong linear relationship with weight carried.

The analyses of the data for the individual studies summarized here yielded significant effects of weight carried on stride frequency in only two of the four studies. Where significant differences were obtained, stride frequency did not vary in an ordered fashion with load weight. The correlation calculated on the pooled data from all four studies was very low, indicating a negligible relationship between stride frequency and load weight. Obusek and Bensel (1998) failed to obtain changes in stride frequency as a function of load weight in their study of the carrying of loads by soldiers. Obusek and Bensel theorized that, because the volunteers were soldiers, they chose a typical military marching step length of 76 cm during the gait trials and maintained the desired velocity by adjusting stride frequency. The use of soldiers as participants may also have impacted the temporal gait variables in the study conducted by Harman et al. (2000) and may have led to the fairly consistent stride frequency observed in the studies reviewed here.

The results presented here for the postural and temporal gait parameters indicate that, although there are not strong linear relationships, changes in weight carried are associated with kinematic adjustments that may aid the load carrier in maintaining stability and in absorbing some of the forces of ground contact. The performance, energy cost, and kinetic variables revealed more marked linear components in their relationships with load weights than the kinematic variables did. Increases in weight carried resulted in substantial increases in times to traverse a 3.2-km course. This decrement in maximal performance is consistent with the increase in energy expenditure also obtained with increasing loads on the body. The fact that, as weight carried increases, traversal times and energy cost increase as well, illustrates the severe negative impact the carrying of loads can have on a soldier's performance in the field and, therefore, on the outcome of military operations. Furthermore, the data presented here on the kinetics of marching with loads show the substantial increases in magnitude of the forces imposed on the body as load weight increases, which likely increase the risk of lower extremity injury.

The analyses reported here, based upon data from four studies employing an identical testing protocol, are relatively extensive, both as to the many levels of load weight and the number of dependent measures examined. There are, however, limitations in the approach taken in this work. For one, simple linear correlation and regression analyses were employed. In addition, total load on the body was examined, and the manner in which the weight was distributed was not considered. Furthermore, different designs of load-carriage systems were used in the different studies, and analyses were carried out in the individual studies to assess design effects. However, the effects of system design and possible interactions between weight carried and system design were not investigated in the analyses of the pooled data reported here. Finally, the participants in the studies had not engaged in strenuous physical exercise prior to data-collection sessions. Soldiers in the field often carry loads for prolonged periods of time. Testing soldiers both before and after fatiguing military activities may lead to a fuller understanding of the impact of load weight on performance.

Conclusions

As the weight of loads soldiers are asked to carry increases, the goals of improved physical performance (e.g., covering greater distances in less time) and injury reduction clearly become harder to reach. Increasing the weight of loads carried by soldiers leads to an increase in the energy cost associated with locomotion. This increase is reflected in slower maximal speed efforts for the 3.2-km run/walk. Increased load weight is also associated with a number of biomechanical changes in walking gait, some of which are kinematic adaptations likely to aid the load carrier in maintaining balance and absorbing the higher forces on the body concomitant to carrying extra weight. The most important biomechanical change related to injury potential is the increase in joint loading with increasing weight carried. Over the range of loads examined, these increases were linear with slopes for the maximum joint forces close to 1.0. Thus, for injury prevention, as well as for increased efficiency of movement, it is important to limit the overall loads carried by a soldier as much as the mission permits. A greater understanding of the implications of weight on military operations and the well-being of soldiers may be gained from studying soldiers engaged in prolonged periods of load carrying.

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